UTM/RMC/F/0024 (1998)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN
LAPORAN AKHIR PENYELIDIKAN

TAJUK PROJEK : THE EFFECT OF CATALYST ON SOIL STABILIZATION BY APPLICATION OF LIME

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THE EFFECT OF CATALYST ON SOIL STABILIZATION BY APPLICATION OF LIME

(KESAN MANGKIN TERHADAP PENSTABILAN TANAH DENGAN APLIKASI KAPUR)

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2009

ACKNOWLEDGEMENT

I would like to thank my friends and my research assistance for their hard working and sharing of knowledge in making this project a successful research. This fundamental research is believed able to provide knowledge on lime stabilization to the civil engineering communities.

Special thanks to the geotechnical laboratory technicians for their support and assistance.

ABSTRACT

THE EFFECT OF CATALYST ON SOIL STABILIZATION BY APPLICATION OF LIME

(Keyword: lime stabilization, kaolinite, zeolite)

Soft cohesive clays are normally associated with large settlements and low strength. Various techniques are available to reduce the problem. One of the low cost techniques is to modify the soil with lime in-situ to make it workable for construction and allow it to increase in strength by pozzolanic reactions between lime and clay minerals. The addition of lime to a soil has a pronounced effect on its physical and chemical properties. It is known to be an effective stabilization method for clayey soil. However, due to the variation of soil minerals and clay fraction, the degree of pozzolanic reactions varies. Addition of catalyst i.e. zeolite may improve the performance of lime stabilization. There are two types of zeolites which are natural zeolite and synthetic zeolite. A series of laboratory tests has been carried out to investigate the effect of zeolite on the performance of lime stabilization. Unconfined Compressive Test on 36 sets of samples has been carried out for 0,7,14, 28 and 56 days of curing. The addition of synthetic zeolite in lime-kaolin stabilized soil has increased the soil strength by 255% at 56 days curing period at the design mix of kaolin + 6% lime +15% zeolite. The higher value of UCS indicates that zeolite is an effective catalyst to enhance lime stabilization.

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ABSTRAK

KESAN MANGKIN TERHADAP PENSTABILAN TANAH DENGAN APLIKASI KAPUR

(Kata Kunci: penstabilan kapur, kaolinite, zeolite)

Tanah liat berjelekit selalu mengalami pengenapan yang besar dan mempunyai kekuatan ricih yang rendah. Terdapat pelbagai kaedah untuk mengurangkan masalah tersebut. Salah satu kaedah yang ekonomi ialah pengubahsuaian insitu dengan kapur terhidrat untuk meningkatkan kebolehkerjaan tanah dan kekuatan tanah melalui tindakbalas pozzolanik antara kapur dan garam-galian di dalam tanah liat. Penggunaan kapur dalam penstabilan tanah liat telah diketahui umum dapat memberi kesan yang baik terhadap struktur fizikal dan kimia tanah tersebut. Walaubagaimanapun, merujuk kepada kepelbagaian garam galian tanah dan struktur dalam tanah tersebut, kadar tindakbalas pozzolanik adalah berbeza di antara setiap jenis tanah. Pertambahan mangkin seperti zeolite adalah sangat efektif untuk meningkatkan prestasi penstabilan batu kapur. Terdapat dua jenis zeolite iaitu zeolite semulajadi dan zeolite sintetik. Suatu siri ujikaji makmal telah dijalankan untuk memastikan kesan pertambahan zeolite ke atas penstabilan kapur. 36 set sampel Ujian Mampatan tak Terkurung telah dijalankan setelah sampel-sampel di awet selama 0, 7, 14, 28 dan 56 hari. Pertambahan zeolite sintetik dalam penstabilan tanah-kapur telah meningkatkan kekuatan tanah sebanyak 255% setelah di awet selama 56 hari pada campuran optimum kaolin + 6% kapur + 15% zeolite A. Peningkatan kekuatan tanah menunjukkan pengggunaa zeolite dalam penstabilan tanah-kapur adalah efektif.

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Soil stabilization using lime or cement has long been used to improve the handling and mechanical characteristics of soils for civil engineering purposes (Sherwood, 1993). Stabilization must then be considered as having both a physical and aspect involving changes to the mechanical properties of the material, and a chemical aspect involving changes to the form and mobility of the contaminants present. The creation of full lime stabilization requires a significant percentage of lime to be added to and mixed with the clay, an adequate understanding of the reaction processes and a good knowledge of the compaction process. It thus requires careful design and close attention to detail during the construction process in order to ensure that the long-term benefits are achieved.

The important of a basic decision must therefore to take into account whether to use the original site material and design to standard sufficient by its existing quality or ; to replace the site material with the superior material or ; create a new site material that suite to the standard requirement by alter the properties of existing material (Ingles, 1972). The stabilizing effect depends on the reaction between lime and soil minerals. The main effect of this reaction is an increasing of shear strength and bearing capacity of the soils.

Soil can be stabilized by the addition of small percentages, by weight, of lime, thereby enhancing many of the engineering properties of the soil and producing an improved construction material. Nowdays, there is a lot of discussion concerning the pozzolanic activity of natural zeolite. Zeolite tuffs have been widely used, as mixtures with lime, in construction since Roman times. Zeolitized tuffs displays excellent pozzolanic activity. This behavior has been exploited, unconsciously, since at least at the beginning of this century.

1.2 Problem Statement

Soil stabilization with lime products will turn unsuitable soils into useful construction materials that can be easily placed and compacted to form part of the temporary or permanent works. Previous works on lime stabilization proved that some type of soil may improved but some may not. This is due to the variation in clay fraction and soil minerals. To extend this finding, lime with addition of catalyst were examined for soil stabilization. Addition of catalyst such as zeolite may improve the long term performance of lime stabilization due to the enhancement in the pozzolanic reaction. Optimum mix of lime and zeolites will be established for effective stabilization.

1.3 Objectives

Generally, the objectives of this study are:

i. To investigate the effectiveness of lime-zeolite in stabilizing soil.
ii. To establish the optimum mix of lime and zeolite additives for effective soil stabilization.
iii. To compare two types of zeolite for effective stabilization.

1.4 Scope of The Study

This study focused on the strength characteristic of the soil by using unconfined compression test. The soils that been used in this study are kaolin. Several tests that have been conducted on soil samples are to identify the engineering properties of samples. Lime that have been used in this study is calcium hydroxide $(CaOH)_2$, also known as hydrated lime or slake lime, since it is not too exothermic and harmful to the skin compared with quicklime. To extend this finding in application, various proportion of lime with additives of zeolite were examine for soil stabilization. There are two types of zeolite which is zeolite A (in powder form) and zeolite B (in granular form) will be used in this study. The concentration of lime were 6% whereas the zeolites are 5%, 10% and 15% performed on samples at curing periods of 0, 7,14,28 and 56 days. Compaction test and Unconfined Compression Test (UCT)also been conducted on the mixture of lime-zeolite.

CHAPTER 2

LITERATURE REVIEW

2.1 Fundamental of Soil Behavior

In geotechnical field, an engineer will works with soil which consist of the entire thickness of the earth crust. All soil are natural aggregate of mineral grains which can be separated by gentle agitation in water. Soil grains are separately by size into four general classifications: gravel, sand, silt, and clay. Gravel and sand are referred to as coarse grained soil, while silt and clay are referred to as fine grained soils. In their natural state soil masses are rarely homogeneous and contain both coarse and fine grained fractions. Such soils are referred to as mixed grained. Mineralogy is the primary factor controlling the size, shape, physical and chemical properties of soil particles.

2.2 Clay

Clay makes up the finer proportion of the fine grained fraction of soils and it is the end product of the chemical decomposition of rock. The mineralogy and molecular arrangement of a clay particle are extremely complex and highly variable.

This gives rise to a considerable range of characteristics within the overall family of clays. Clays are subdivided, therefore, into several groups that differentiate one clay type from another. From the geotechnical engineering viewpoint, clay is a kind of cohesive soil which is very weak and its strength will decrease by influence of climate or water content in the soil.

The solid phase of soil may contain various amounts of crystalline clay and nonclay minerals, noncrystalline clay mineral, organic matter, and precipitated salts. The crystalline minerals comprise the greatest proportion in most soil encountered in engineering practice, and the amount of nonclay material usually exceeds the amount of clay. Nonetheless, clay and organic matter in a soil usually influence properties in a manner far greater than their abundance.

Silicates (feldspars), oxides (silica and iron), carbonates (calcium and magnesium), and sulphates (calcium) are the common minerals of clay. The mineralogical composition of clays range from kaolins (made up of individual particles which cannot be readily divided, through illites to montmorillonites and other non-sheet-clay minerals (T.S Nagaraj & Norihiko Miuro, 2001). Kaolins made up of individual particles which cannot be readily divided. Illite is another important constituents of clay soils which have a crystal structure similar to the mica minerals but with less potassium; thus they are chemically much more active than other mica (Robert D. Holtz, 1981).

2.3 Kaolinite

Kaolinite is a clay mineral with the chemical composition $Al_2Si_2O_5(OH)_4$. Kaolinite made up of individual particles which cannot be readily divided and it is a layered silicate mineral, with one tetrahedral sheet linked through oxygen atoms to one octahedral sheet of alumina octahedral. Rocks that are rich in kaolinite are known as china clay or kaolin. Kaolinite has a low shrink-swell capacity and a low cation exchange capacity (1-15 meq/100g.) It is a soft, earthy, usually white mineral (dioctahedral phyllosilicate clay), produced by the chemical weathering of aluminium silicate minerals like feldspar. In many parts of the world, it is colored pink-orange-red by iron oxide, giving it a distinct rust hue. Lighter concentrations yield white, yellow or light orange colours.

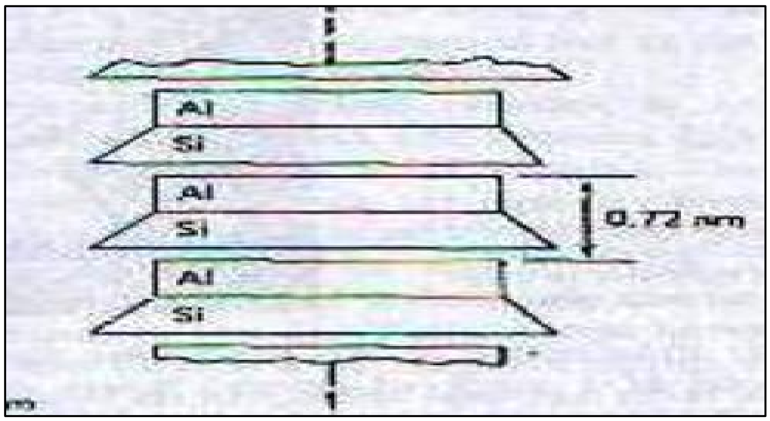

Figure 2.1: Schematic diagram of kaolinite structure

Figure 2.2: Kaolinite

Chemical formula	$Al_2Si_2O_5(OH)_4$
Color	White, sometimes red, blue or brown tints from impurities
Crystal habit	Earthy
Crystal system	triclinic
Cleavage	perfect on {001}
Fracture	Perfect
Mohr Scale hardness	2 - 2.5
Luster	dull and earthy
Refractive index	α 1.553 - 1.565, β 1.559 - 1.569, γ 1.569 - 1.570
Streak	white
Specific gravity	2.16 - 2.68

Table 2.1 : Identification of kaolinite (Klain and Cornelis, 1985)

2.4 Lime Stabilization

2.4.1 Introduction

Soil stabilization using lime is known to be one of the method to increase the shear strength of soils. It has long been used to improve the handling and mechanical characteristics of soils for engineering purposes (Sherwood, 1993). There are two types of lime which is CaO (quicklime or burnt lime) and $Ca(OH)_2$

(slake or hydrated lime). Lime was first used as a stabilizing agent of soil in modern construction practice in 1924 on short stretches of highway strengthened by the addition of hydrated lime (Bell, 1996). The use of lime, as chemical additives is to improve soil properties as to dry, modify and stabilize soil. It is a well established construction technique. The stabilizing effects depends on the reaction between lime and the clay minerals. By using lime for soil stabilization, a number of benefits are obvious such as an increase in the shear strength and bearing capacity of the soil, a reduction in the susceptibility to swelling and shrinkage, an improvement in the resistant to bad weather and reduce the moisture content in order to improve the workability and compaction characteristics.

2.4.2 Effect of lime on soil

Lime has a number of effects when added into soil, which can be generally categorized as soil drying, soil modification and soil stabilization.

i. Soil drying is a rapid decrease in soil moisture content due to the chemical reaction between water and quicklime and the addition of dry material into a moist soil.

ii. Modification effects include reduction in soil plasticity, increase in optimum moisture content, decrease in maximum dry density, improved compactibility, reduction of the soil's capacity to swell and shrink, and improved strength and stability after compaction.

iii. Lime stabilization occurs in soil containing a suitable amount of clay and the proper mineralogy to produce long term strength ; and permanent reduction in shrinking , swelling, and soil plasticity with adequate durability to resist the detrimental effects of cyclic freezing and thawing and prolonged soaking. Lime stabilization occurs over a longer time period of “curing”.

2.4.3 Mechanism of Lime Stabilization

Three mainly reactions which give a major strength gain of lime treated clay are dehydration of soil, ion exchange and flocculation, and pozzolanic reaction. Mechanisms such as carbonation only cause minor strength increase of soil and can be neglected. The use of lime as a natural stabilizing agent for clay will produce a binder by slow chemical reactions mainly with silicates in the clay mineral (Broms, 1984). $Ca(OH)_2$ formed due to hydration process when lime (CaO) is added to soil (Koslanant, Onitsuka & Negami, 2006). During the hydration process, larger amount of pore water evaporates because of the heavy heat release induced by an increase of temperature (Miura & Balasubramaniam, 2002).

$$\boxed{\mathbf{CaO + H_2O \longrightarrow Ca(OH)_2 + HEAT\ (280\ Cal/gm\ of\ CaO)}}$$

Moreover in order to make the ion exchange possible between calcium ions of hydrated lime and the alkali ions of the clay minerals, water left after evaporation must be sufficiently enough. Therefore, it is vital to know that water content of the base clay enough. An exchange of ions between clay minerals and lime depends on cation exchange capacities (i.e. concentration of calcium ions) which highly depend on the pH of the soil water and the type of clay mineral. Based on Bergado (2002) montmorillonites have the highest capacity compared to illite and kaolinite. Hence, lime will caused clay to flocculate thus make the clay plasticity reduced and making it more workable as well as increased its strength (Koslanant, Onitsuka & Negami, 2006). The results in the flocculation of the clay particles is caused by dissociated bivalent calcium ions in the pore water replacing univalent alkali ions that normally attracted to the negatively charged clay particles.

$$Ca^{++} + \text{Clay} \longrightarrow Ca^{++} \text{ exchanged with monovalent ions } (K^{+}, Na^{+})$$

New compounds such as calcium silicate hydrate and calcium alluminate hydrates gels are formed as a result of pozzolanic reactions in which subsequently crystallize to bind the structure together (Rogers & Glendinning, 1997). These reactions take places as hydroxyl ions released from the lime which in turn dissolved silica and alumina from the clay minerals.

$$Ca^{++} + 2(OH)^{-} + Al_2SiO_3 \longrightarrow CAH$$

$$Ca^{++} + 2(OH)^{-} + SiO_2 \longrightarrow CSH$$

2.4.4 Factors Controlled the Hardening Characteristics of Lime Treated Clay

i. Type of Lime:

As mentioned previously, quicklime is generally more effective than hydrated lime. However it needs care in handling for soils with high moisture contents. Therefore the used of hydrated lime become necessary because it poses much less of storage problem as it is no longer so susceptible to humidity (O.G.Ingles, 1972). Furthermore, hydrated lime is recommended for organic soils in order to gain the strength of that particular soil (Moseley & Kirsch, 2005). This is because; the reaction of the organic material will reduce the pH and the pozzolanic reactions.

ii. **Optimum Lime Content:**

Note, the strength of soil will increase as the lime content is increased. However, until a certain level, the rate of increase then diminishes until no further strength gain occurs. For a particular condition of curing time and soil type, there is a corresponding optimum lime content which causes the maximum strength increase (Balasubramaniam, 2002).

iii. **Lime Fixation Point:**

The lime fixation point or can also referred as the “lime retention point”. This is explained by the point at which the percentage of lime is such that additional increments of lime remain constant in the plastic limit. Even though at this point, soil will generally contribute to the improvement in soil workability, but strength of soil results no increases (Bergado, Anderson, Miura, Balasubramaniam, 2002).

iv. **Curing Time:**

In almost all the other cases the length of time involved in curing generally rise in strength with increasing length of curing time. Based on research done by Bell (1996), the most notable increases in strength occur within the first 7 days when pozzolanic reactions are more active.

v. **Type of Soil:**

For lime treatment to be successful, the shear strength of the clay soil is highly dependent on pozzolanic reactions due to reactions of lime with the silicates and aluminates in the soil.

vi. **Soil pH:**

Solubility of soil will increase with the increase of pH of the water content in soil by addition of lime. Due to the increased solubility of the silicates and aluminates, the pozzolanic reactions will accelerate thus give pH-value more than 12 (Broms, 1984). Study done by Davidson (1965), has suggest that a minimum pH of approximately 10.5 is necessary for pozzolanic reaction to take place. The high alkaline environment promotes the dissolution of silica and alumina from the clay particles.

vii. Curing Temperature:

The influence of curing temperature on the development of strength is favored by a high temperature (George, Ponniah & little, 1992). The favorable effect of high curing temperature is due to the increased solubility of the silicates and aluminates in the clay (Bergado, Anderson, Miura, Balasubramaniam, 2002).

2.4.5 Effect Of Sulphate in Soil-Lime Reactions

It is important to know that the presence of sulphates either in ground or mixing water may affect the cation exchange and pozzolanic reactions of lime treated soil systems (Rajasekaran, 2005). The atterberg limits and compaction characteristics of lime treated clay will be influenced by the reaction of cation exchange. This is due to the broken bonds f soil particle edges and unbalanced ionic substitution within the clay mineral lattice result in increasing negative cahtges of soil system.

The sulhates, for example gypsum, react with lime and cause swelling which can be danger to the material’s strength and cause deformation of any final surface (Perry, Macneil & Wilson, 1996). Cations, concentration of sulphates and clay minerals composition (available alumina and silica) are the several factors that influence the lime treated soil properties.

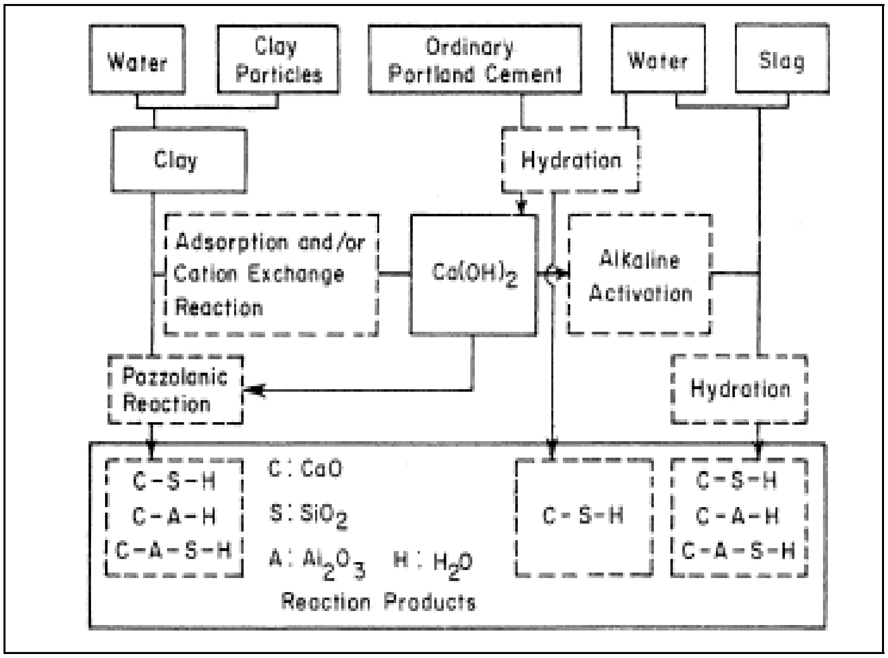

Figure 2.3: Reaction mechanisms involved in the hardening effect of improved soil (after Rajasekaran, 2005)

2.5 Zeolite

Zeolites are microporous, aluminosilicate minerals commonly used as commercial absorbents. Compositionally, zeolites are similar to clay minerals. More specifically, both are alumino-silicates. They differ, however, in their crystalline structure. Many clays have a layered crystalline structure (similar to a deck of cards) and are subject to shrinking and swelling as water is absorbed and removed between the layers. In contrast, zeolites have a rigid, 3-dimensional crystalline structure (similar to a honeycomb) consisting of a network of interconnected tunnels and cages. Water moves freely in and out of these pores but the zeolite framework remains rigid. Another special aspect of this structure is that the pore and channel sizes are nearly uniform, allowing the crystal to act as a molecular sieve. The porous zeolite is host to water molecules and ions of potassium and calcium, as well as a variety of other positively charged ions, but only those of appropriate molecular size to fit into the pores are admitted creating the "sieving" property.

One important property of zeolite is the ability to exchange cations. This is the trading of one charged ion for another on the crystal. One measure of this property is the cation exchange capacity (CEC). Zeolites have high CEC's, arising during the formation of the zeolite from the substitution of an aluminum ion for a silicon ion in a portion of the silicate framework (tetrahedral units that make up the zeolite crystal).

When developing applications for zeolites, it is important to remember that not all of these minerals are the same. It is critical to understand how zeolites differ so that only the appropriate types and source materials are selected for each application. There are nearly 50 different types of zeolites (clinoptilolite, chabazite, phillipsite, mordenite, etc.) with varying physical and chemical properties.

Crystal structure and chemical composition account for the primary differences. One difference between zeolites worth giving special mention is the composition of exchangeable cations residing in the zeolite. Exchange sites on natural zeolites are primarily occupied by 3 major cations: potassium (K), calcium (Ca), and sodium (Na) (other elements such as magnesium (Mg) may also be present). Exchange sites on a particular zeolite may contain nearly all K, nearly all Na, some Ca or Mg, or a combination of these. Particle density, cation selectivity, molecular pore size, and strength are only some of the properties that can differ depending on the zeolite in question.

Figure 2.4: Zeolite

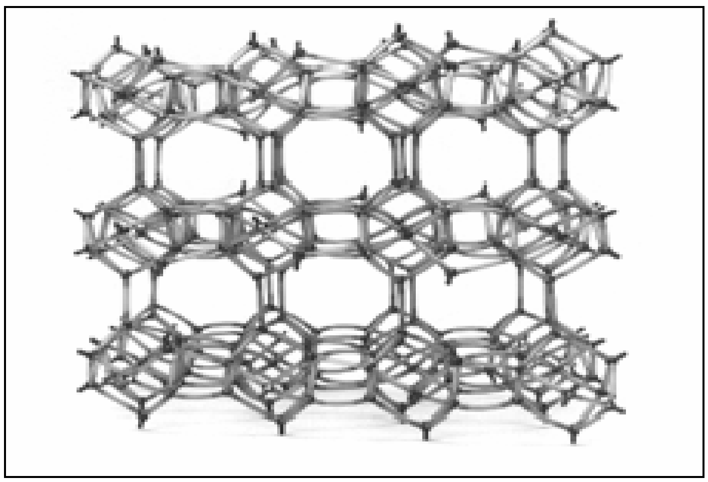

Figure 2.5: Zeolite framework model (view along cleavage plane of crystals plates)

2.5.1 Types of zeolite

There are two types of zeolite which is natural zeolite and synthetic zeolite. Natural zeolites form where volcanic rocks and ash layers react with alkaline groundwater. Zeolites also crystallize in post-depositional environments over periods ranging from thousands to millions of years in shallow marine basins.

Naturally occurring zeolites are rarely pure and are contaminated to varying degrees by other minerals, metals, quartz, or other zeolites. For this reason, naturally occurring zeolites are excluded from many important commercial applications where uniformity and purity are essential.

There are several types of synthetic zeolites that form by a process of slow crystallization of a silica-alumina gel in the presence of alkalis and organic templates. One of the important processes used to carry out zeolite synthesis is sol-gel processing. The product properties depend on reaction mixture composition, pH of the system, operating temperature, pre-reaction 'seeding' time, reaction time as well as the templates used. In sol-gel process, other elements (metals, metal oxides) can be easily incorporated. The silicalite sol formed by the hydrothermal method is very stable. Also the ease of scaling up this process makes it a favorite route for zeolite synthesis.

Synthetic zeolites hold some key advantages over their natural analogs. The synthetics can, of course, be manufactured in a uniform, phase-pure state. It is also possible to manufacture desirable zeolite structures which do not appear in nature. Zeolite A is a well-known example. Since the principal raw materials used to manufacture zeolites are silica and alumina, which are among the most abundant mineral components on earth, the potential to supply zeolites is virtually unlimited. Finally, zeolite manufacturing processes engineered by man require significantly less time than the 50 to 50,000 years prescribed by nature. Disadvantages include the inability to create crystals with dimensions of a comparable size to their natural counterparts.

2.5.2 Influence of Zeolite Additives

Zeolite additives to lime stabilization may increase the strength of mixture. The addition is as pozzolans that act as catalyzer to accelerate as well as help lime to increase the strength of soil. A pozzolan is a material which, when combined with calcium hydroxide, exhibits cementitious properties. Pozzolans are primarily vitreous siliceous materials which react with calcium hydroxide to form calcium silicates; other cementitious materials may also be formed depending on the constituents of the pozzolan.

A pozzolan is a siliceous or aluminosiliceous material(such as zeolite), which is highly vitreous. This material independently has few/fewer cementitious properties, but in the presence of a lime-rich medium like calcium hydroxide, shows better cementitious properties towards the later day strength (> 28 days). The mechanism for this display of strength is the reaction of silicates with lime to form secondary cementitious phases (calcium silicate hydrates with a lower C/S ratio) which display gradual strengthening properties usually after 7 days.The extent of the strength development depends upon the chemical composition of the pozzolan: the greater the composition of alumina and silica along with the vitreous phase in the material, the better the pozzolanic reaction and strength display.

Many pozzolans available for use in construction today were previously seen as waste products, often ending up in landfills. Use of pozzolans can permit a decrease in the use of Portland cement when producing concrete, this is more environmentally friendly than limiting cementitiuos materials to Portland cement. As experience with using pozzolans has increased over the past 15 years, current practice may permit up to a 40 percent reduction of Portland cement used in the concrete mix when replaced with a carefully designed combination of approved pozzolans. When the mix is designed properly, concrete can utilize pozzolans without significantly reducing the final compressive strength or other performance characteristics.

CHAPTER 3

METHODOLOGY

3.1 Introduction

A testing series has been done in order to achieve the project objectives. Classification for suitability tests has been carried out on soil and lime in the laboratory to ensure the soil is suitable for stabilization and adequate amount of lime to be used. The classification test for soil are specific gravity, Atterberg limit and particle size distribution whereas the suitability test for lime are initial consumption of lime and available lime content. An eight (8) sets of compaction test has been carried out on the mixture of soil-lime-zeolites to obtain the maximum dry density (MDD) and optimum moisture content (OMC). This value is important for sample preparation for Unconfined Compressive Test (UCT) that has been done after curing at 0, 7, 14, 28 and 56 days. 36 sets of UCT have been tested to investigate the effect of lime stabilization with zeolites additives ranging from 5%, 10% and 15% on the strength development. All the laboratory testing on lime and soil are carried out in accordance with BS1377 (1990): Part 1, Part 2, Part 3 and Part 4 and BS1924 (1990): Part 1 and Part 2. Figure 2.1 (enclosed) showing the methodology flow chart. Figure 3.1 showing the methodology flow chart.

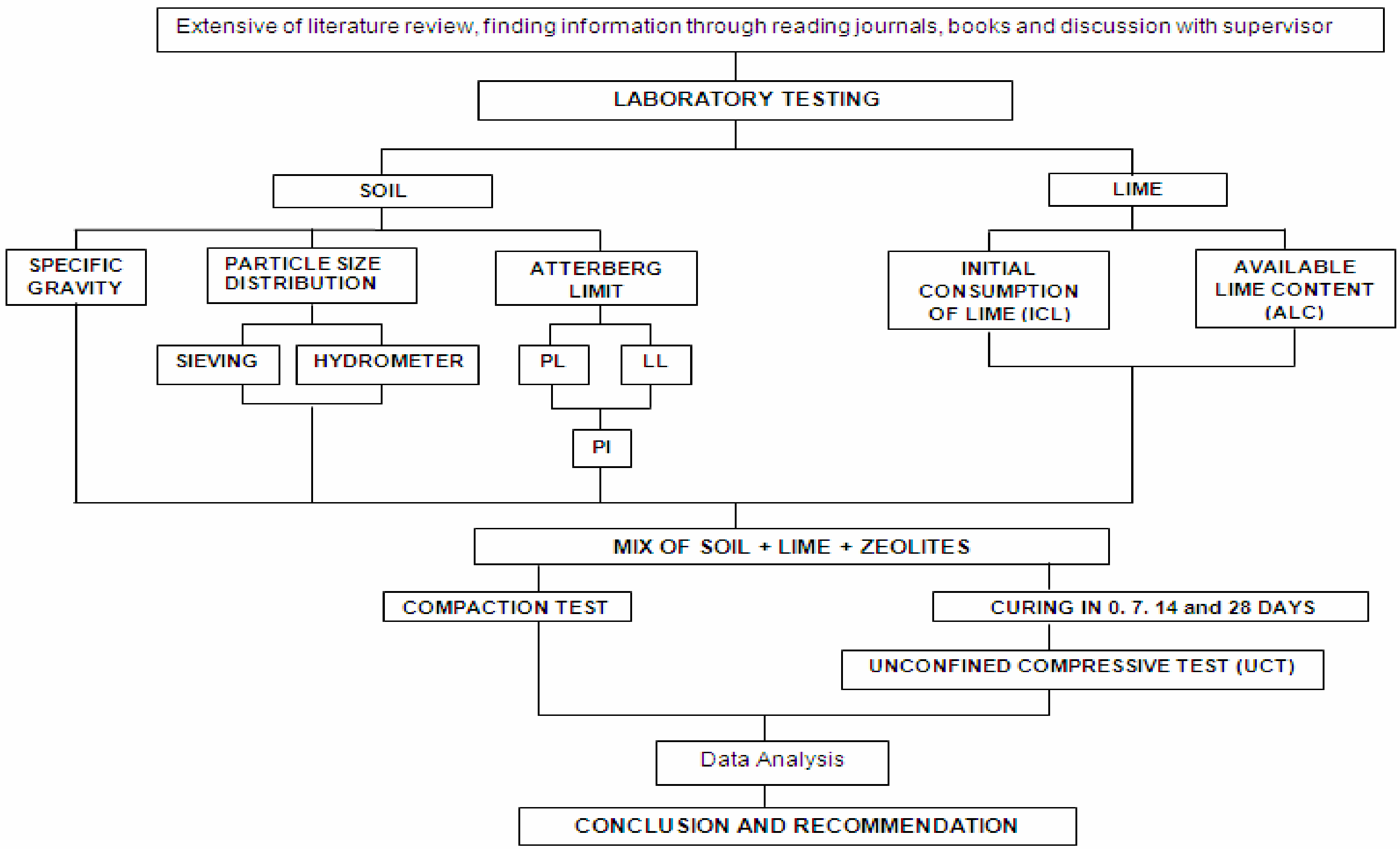

Figure 3.1: Methodology Flow Chart

3.2 Soil classification tests:

soil classification tests is carried out to evaluate key soil characteristics as an initial step to determine either it is suitable for lime stabilization. The detailed explanation on each testing are as follows:

3.2.1 Specific Gravity

Based on BS1377:1990, the aim of this test is to define the average specific gravity (Gs) that useful for determining the weight-volume relationship. It is the ratio between the unit masses of soil particles and water. Determination of the volume of a mass of dry soil particles is obtained by placing the soil particles in a glass bottle filled completely with desired distilled water. The bottles and it contents are shaken (for coarse-grained soils) or placed under vacuum (for finer-grained soils) in order to remove all of the air trapped between the soil particles. Figure 3.2 shows the specific gravity vacuum.

Figure 3.2: Specific gravity vacuum

3.2.2 Particle Size Distribution

The method to determined particle sizes distribution is defined in BS 1377: Part 2: 1990 to check that there is an adequate content of material passing 63 microns. The mixture of different particle sizes and the distribution of these sizes give very useful information about the engineering behaviors of the soil. The particle size distribution is determined by separate the particles using two processes which is sieving analysis or hydrometer analysis. Sieve analysis for particle sizes larger than 0.075mm in diameter; and hydrometer analysis for particle sizes smaller than 0.075mm in diameter are the method usually used to find size distribution of soil.

3.2.2.1 Sieve Analysis:

The grain size distribution curve of soil samples is determined by passing them through a stack of sieves of decreasing mesh-opening sizes and by measuring the weight retained on each sieve. The analysis also can be performed either in wet or dry conditions. Soil with negligible amount of plastic fines, such as gravel and clean sand will analysed by dry sieving while wet sieving is applied to soils with plastic fines.

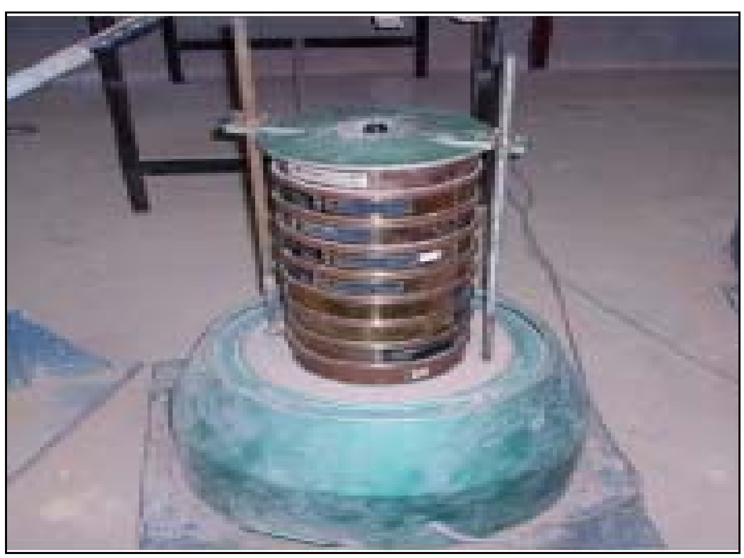

Figure 3.3: A set of sieves

3.2.2.2 Hydrometer Analysis:

Hydrometer analysis is based on the principles expressed by Stokes' law which it is assumed that dispersed soil particles of various shapes and sizes fall in water under their own weight as non-interacting spheres.

Figure 3.4: Mechanical Shaker

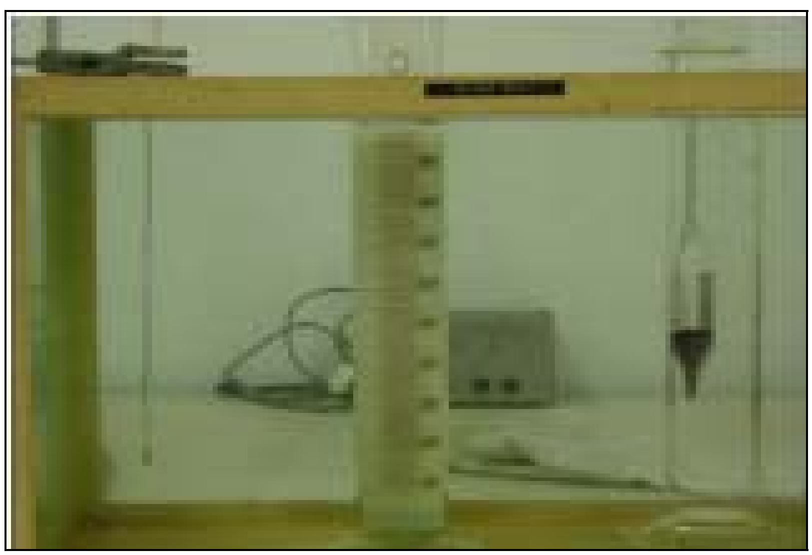

Figure 3.5: Hydrometer Reading

3.2.3 Atterberg Limit

It is important to carry out several simple tests to describe the plasticity of clay toavoid shrinkage and cracking when fired. Atterberg limit described an amount of water contents at certain limiting or critical stages in soil behavior. If we know where the water content of our sample is relative to the Atterberg limit, that we already know a great deal about the engineering response of our sample. This test was carried out in order to determine the stiffness of clay and parameters measured are plastic limit (PL) and liquid limit (LL). The behavior of soil in term of plasticity index (PI) is determined by using this formula:

$$PI = LL - PL$$

3.2.3.1 Plastic Limit

Plastic Limit represent the moisture content at which soil changes from plastic to brittle state. It is upper strength limit of consistency. Casagrande (1932) suggested that the simple method to do this test is by rolling a thread of soil on a glass plate until it crumbles at a diameter of 3 mm. Sample will reflects as wet side of the plastic limit if the thread can be rolled in diameter of below 3 mm, and the dry side if the thread breaks up and crumbles before it reaches 3 mm diameter.

Figure 3.6: Plastic Limit test

3.2.3.2 Liquid Limit

Liquid limit is expressed in terms of water content as a percentage. It is essentially a measure of a constant value of a lower strength limit of viscous shearing resistance as the soil approaches the liquid state. As described in most books in soil mechanics, cone penetrometer method (BS1377: 1990) is the most reliable method for determining a liquid limit.

The equipment consists of a 30^o cylindrical cone with a sharp point and a smooth polished surface. The total mass of 80 g is allowed to fall freely will penetrate a distance of 20 mm in 5 seconds from a position of points contact with further additions of distilled water and a plot of cone penetration versus moisture content is obtained. The liquid limit of the soil is taken as the moisture content at a penetration of 20 mm.

Figure 3.7: Liquid Limit test

3.2.3.3 Plasticity Index

Plasticity index is defined as a range of water content where the soil is plastic. Therefore it is a numerically equal to the differences between the liquid limit (LL) and the plastic limit (PL). Many engineering properties have been found to empirically correlate with the PI, and it is also useful engineeringclassification of fine-grained soils.

3.2.4 Standard Proctor Compaction Test

The procedure for conducting this test is described in BS 1377: Part 4: 1990. The test is carried out to measure the degree of compaction in terms of its dry unit weight. The optimum moisture content then will be determined. The principle of compaction as explained in theory is completely removed the air fraction. However in practice, compaction cannot completely eliminate the air fraction, but only reduces it as minimum as it can be.

Water will act as a softening agent when it is added to the soil particles. This situation will makes the soil particles slip over each other and move into densely packed position. After compaction, the dry unit weight is increase as the moisture content increase. However, at certain level of moisture content, any increase in the moisture tends to reduces the dry unit weight of soil. This is the results of water that takes up spaces that would have been occupied by the solid particles. Optimum moisture content (OMC) then is referred to the moisture content at which the maximum dry density (MDD) is attained.

The soil is compacted in three layers with equal thickness into a metal of 105 mm diameter and of 1L or 1000 cm^3 capacity. 2.5 kg mass falling freely through each layer at a height of 300 mm with 25 blows in the one liter mould. In order to ensure the final layer is compacted, the surface must lies just above the top of the mould. The mould and soil are weighted after the soil surface is trimmed with the top of the mould so that its volume can be taken as 1L. The bulk density or unit weight of the soil can be determined by subtracting the weight of the mould.

At least five density values are needed before the optimum moisture content is obtained. The dry density of the soil is calculated and plotted versus moisture. Instead to know the OMC and MDD of soil, the determination of OMC and MDD also necessary to get after lime has been added to the soil. This is because adding lime will change the soil's OMC and MDD.

3.3 Lime Test

Similarly with soil, lime also need to be tested in order to check their suitability when react with soil. The appropriate and adequate amount of lime should be determined before stabilization process commerce. There are two test commonly performed on lime which is initial consumption of lime (ICL) and available lime content (ALC).

3.3.1 Initial Consumption of Lime (ICL)

This test give an indication of the initial amount of lime needed to achieve sufficient lime should be added to a soil to ensure that a pH of 12.4. The purpose of this test is to evaluate an initial step to determine if it is suitable for lime stabilization. This value plays an important role in order to sustain the strength producing lime-soil pozzolanic reactions. Details procedure explained in BS1924: Part2: Clause 5.4.

Generally, soil with at least passing 25% passing a 75 micron screen and having PI of 10 or greater are candidates for lime stabilization. Some soils with lower PI can be successfully stabilized with lime, provided the pH and strength criteria can be satisfied. The lowest percentage of lime in soil that produces a laboratory pH 12.4 is the minimum lime percentage for stabilizing the soil. Therefore, the lime content must be greater than the ICL value.

3.3.2 Available Lime Content (ALC)

The available lime content either quicklime or hydrated lime is determined based on BS6463: Part 2: Test 20. The present of calcium oxide or calcium hydroxide is made by shaking them with a solution of sucrose. The solution is titrated against standard hydrochloride acid after the residue has been filtered off. Phenolphthalein is used as indicator in the titration. The formulae for indicator to be used are as follow:

Percentage available lime (as CaO) = 2.8045 V / m

Percentage available lime (as $Ca(OH)_2$) = 3.705 V / m

Where,

V = the titration (mL)

M = mass of sample (mg)

3.4 Unconfined Compression Test

The clay in all cases was oven-dried to obtain its initial dry weight after mixing with the required amount of water at optimum moisture content and its respective percentage of hydrated lime. Zero percentage of lime tests refer to investigation not longer than 1 hour after addition of water.

As for fine-grained materials, specimens were prepared and compacted to pre-determined density in a cylindrical steel mould of dimensions 100 mm high x 50 mm diameter having two steel plugs (BS 1924: Part 2: 1990 Section 4). The aim for this test is to determine the strength of the soil treated by lime as well as soil treated by lime-additives salts. It is a special type of unconsolidated-undrained test that is commonly used for clayey specimens. Based on the UCT principle, the confining pressure is equal to zero. Clay specimen will be tested until failure when an axial load is applied rapidly to the specimen. At failure, the total minor principal stress is zero while the total major principal stress is σ_1.

After extrusion, the specimen were stored at room temperature and sealed with paraffin wax in PVC tubes in accordance with BS 1924: Part 2: 1990 to minimize loss of moisture content and also to prevent access carbon dioxide. For each stabilizer content, at least two specimen were tested by compression testing machine at a steady rate of axial deformation of approximately 1 mm / min after 0, 7, 14, 28 and 56 days of curing.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The earth is geologically and geotechnically complex, not only in its interior but also in its surface. Wide variability in the kinds and properties of the soils of engineering concern must be anticipated. The studies aim to develop basic design concept of mix design for the effectiveness of catalyst addition in lime stabilization. Principle of geotechnical engineering, chemistry and physical enable knowledge to be integrated for needs and practices of civil engineering. This chapter presented the results and discussion for the studies aims.

4.2 Soil Classification

4.2.1 Specific Gravity

The aim of this test is to define the average specific gravity (Gs) that useful for determining the weight-volume relationship. It is the ratio between the unit masses of soil particles and water. Based on the table below, the average value of specific gravity is 2.41.

Table 4.1: Summary of data for specific gravity

DESCRIPTION	UNIT	VALUES		
Pyknometer number		1764	1761	1757
Mass of bottle + soil + water (m_3)	g	82.320	82.308	84.662
Mass of bottle + soil (m_2)	g	34.193	35.288	36.608
Mass of bottle full of water (m_4)	g	79.788	78.976	81.004
Mass of bottle (m_1)	g	29.853	29.773	30.337
Mass of soil	g	4.34	5.515	6.271
Mass of water in full bottle	g	49.935	49.203	50.667
Mass of used	g	48.127	47.02	48.054
Volume of soil particles	ml	1.808	2.183	2.613
Particle density	Mg/m^3	2.40	2.53	2.40
Average value Ps	Mg/m^3		**2.41**	

4.2.2 Atterberg Limit

Atterberg Limit described an amount of water content at certain limit or critical stages in soil behavior. The results for Atterberg Limit tests are shown in Appendix A. Based on the Figure 4.1, the liquid limit (LL) of the soil at 20mm penetration is 44.2%.

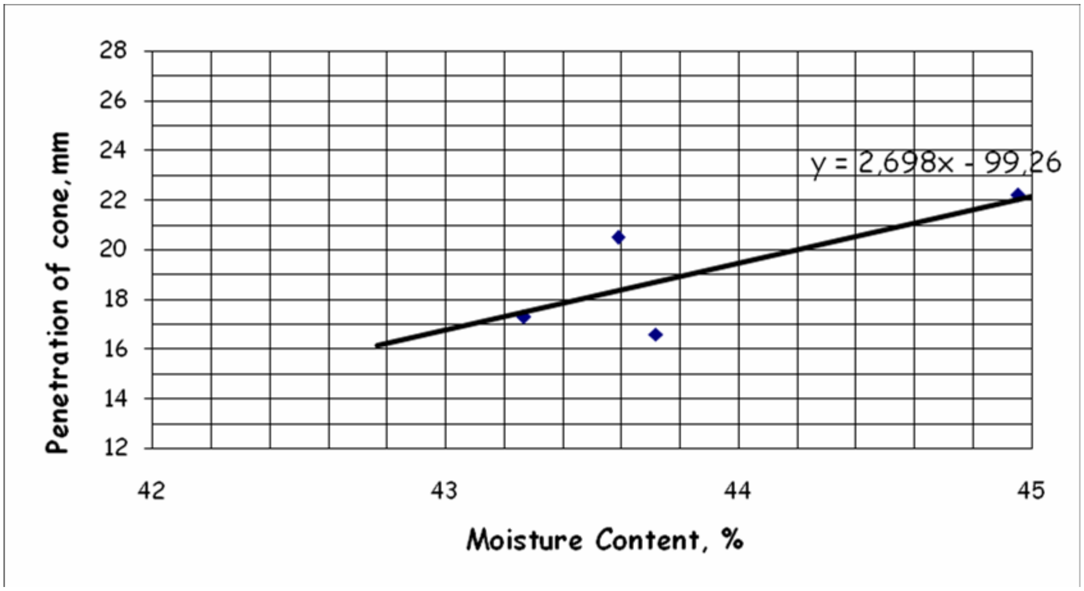

Figure 4.1: Cone Penetration vs Moisture Content

The result of plastic limit (PL) which represent the moisture content at which soil changes from plastic to brittle state is 23.7% determine from oven-dried sample. Plasticity Index (PI) is defined as a range of water content where the soil is plastic. Therefore it is a numerically equal to the difference between the liquid limit (LL) and the plastic limit (PL). The plasticity index of the soil is evaluated as the calculation below.

$$\begin{aligned} PI &= LL - PL \\ &= 44.2 - 23.7 \\ &= 20.5\% \end{aligned}$$

Since the value of PI is higher than 10, this soil meets the requirement to be stabilized with lime. From the Plasticity chart: British System (BS5930: 1999) below, this soil can be classified as CI (Intermediately Clay).

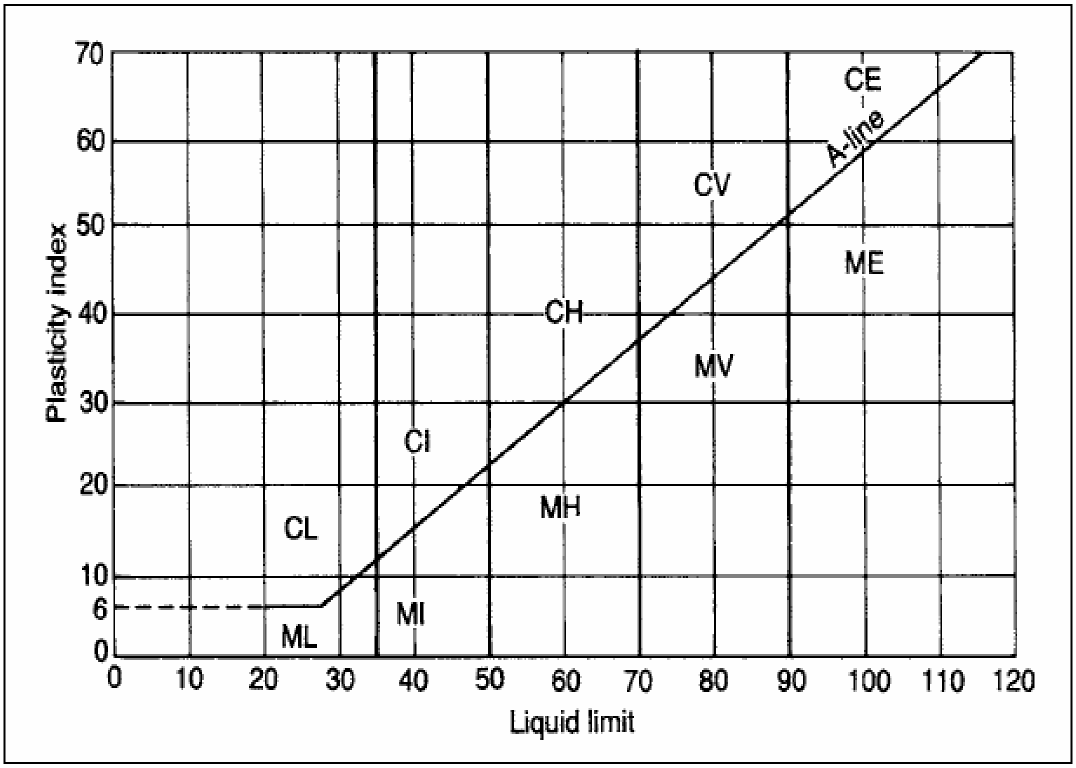

Figure 4.2: Plasticity chart: British System (BS5930: 1999)

4.2.3 Particle Size Distribution

Soils are primarily classified on the basis of particle size. Each of the particles considered will therefore fall into a prescribed size range and will form a soil that is represented by dominant particle size. Particle size is an easy parameter to measure and controls many aspect of the engineering behavior of a soil. Sand and gravel are cohesionless particles that posses no inter-particle bond. Clay and silts are usually cohesive (Pitts, 1984).

Based on the wet sieving and hydrometer analysis, the soil used in this study consists of 4.80% gravel, 14.03% sand and 81.17% of fines grained (70.17% silt and 11% clay). Therefore this soil is suitable to be stabilized with lime as it is categorized as fine grained soil. Besides, the percentage of clay is more than 10%, thus meet the requirement for lime stabilization. Particle size distribution of unstabilized soils is presented in Figure 4.3. Results of the wet sieving, dry sieving and hydrometer test are attached in Appendix A.

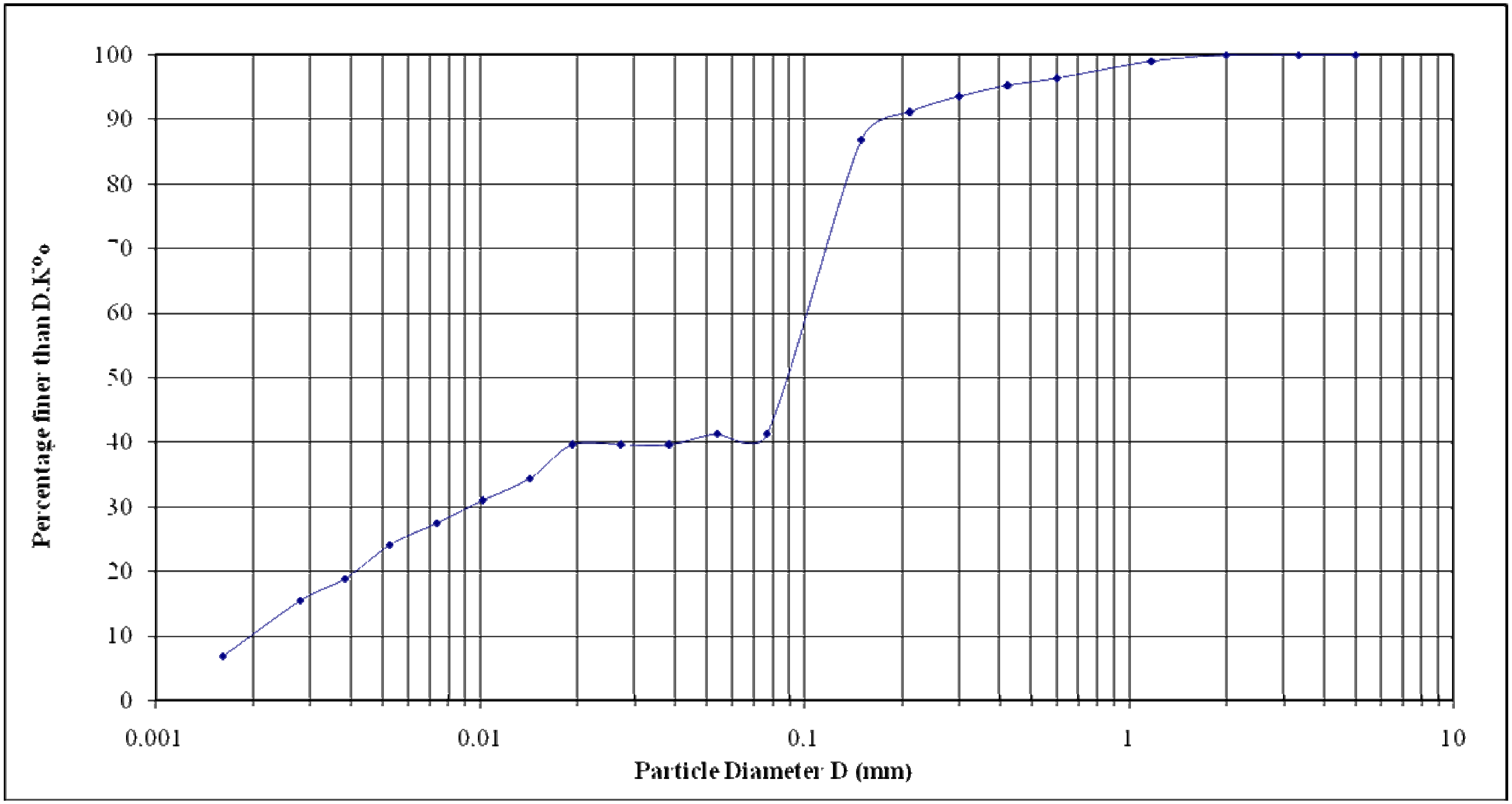

Figure 4.3: Soil Particle Distribution Chart

4.3 Lime Test

4.3.1 Initial Consumption of Lime (ICL)

Lime used in this study is hydrated lime, $Ca(OH)_2$. Inspection of the lime quality used in this investigation is essential as it determines the effectiveness of lime modification and stabilization. Standard means of specifying the content of lime should be used. Initial consumption of Lime (ICL) test indicating that the initial amount of lime needed to achieve sufficient lime should be added to a soil to ensure that a pH of 12.4. Table 4.2 shows the initial consumption of lime data.

	Calcium hydroxide	**Lime used in test**
pH of saturated solution	13.24	13.21
Temperature (^oC)	26.4	26.5
pH corrected to 25 ^oC	13.28	13.26

DESCRIPTION	**VALUES**					
Lime content %	0	1	2	3	4	5
pH value of suspension	6.77	12.79	13.09	13.09	13.14	13.16
Temperature ^oC	25.2	25.2	25.1	25.1	25	25.3
pH corrected to 25 ^oC	6.776	12.796	13.093	13.093	13.14	13.169

Table 4.2: Initial Consumption of Lime test data

From the data attained, 2.0% of hydrated lime is the minimum percentage of lime needed for soil stabilization. This value plays an important role in order to sustain the strength producing lime-soil pozzolanic reaction.

4.3.2 Available Lime Content (ALC)

From the laboratory test:

The titration, V = 33.4 mL

The weight of sample used, m = 1.445 g

Percentage of available lime (as CaO) = 2.804 V / m

= [2.804(33.4)] / 1.445

= 64.8 %

Percentage of available lime (as $Ca(OH_2)$) = 3.705 V / m

= [3.705(33.4) / 1.445]

= 85.6 %

The available lime content in terms of equivalent CaO is 64.8%, which is greater than the minimum requirement of 60%. The available $Ca(OH)_2$ content is 85.6% which is greater than minimum requirement of 80%. Therefore, the hydrated lime that used in this research is suitable for lime stabilization.

4.4 Standard Proctor Compaction Test

Table 4.3 show a result of compaction test perform on kaolin soil, lime treated kaolin soil and lime treated kaolin soil with addition of catalyst at different concentration. The calculation and compaction curves for all of the samples tested are enclosed in Appendix B.

Table 4.3: Compaction Test Result

SAMPLE	**COMPACTION**	
	MDD (Mg/m^3)	**OMC (%)**
Kaolin	1.600	20.0
Kaolin + 6% Lime	1.545	22.7
Kaolin + 6% Lime + 5% Zeolite A	1.583	22.0
Kaolin + 6% Lime +10% Zeolite A	1.490	21.6
Kaolin + 6% Lime +15% Zeolite A	1.482	24.3
Kaolin + 6% Lime + 5% Zeolite B	1.502	21.9
Kaolin + 6% Lime +10% Zeolite B	1.480	23.3
Kaolin + 6% Lime +15% Zeolite B	1.480	22.7

From the results data, the maximum dry density (MDD) and optimum dry density (OMC) were different between each mixture. The addition of zeolite tends to reduce the MDD. The reduction in dry density could be due to the flocculation and agglomeration effect of soil particles which reduce compactibility and hence the density of the treated soil. The OMC generally increases with addition of lime and zeolite compared to the unstabilised soil. This is due to the higher consumption of water for the reaction to take place. When zeolite act as pozzolans, it reduce chloride permeability and improve workability. It reduce weight and helps moderate water content while allowing for slower drying.

4.5 Unconfined Compressive Strength (UCS)

The calculation of the data from unconfined compressive test (UCT) and charts of axial stress versus strain for each concentration at different curing period are shown in appendix D. Table 4.4 shows the summary of the strength result obtained from all of the samples at different curing period.

Table 4.4: Unconfined Compressive Test Result

DESCRIPTION			**UCS (kPa)**		
Curing period (days)	**0**	**7**	**14**	**28**	**56**
Kaolin	215	192	190	208	228
Kaolin + 6% Lime	364	408	485	717	926
Kaolin + 6% Lime + 5% Zeolite A	306	478	440	557	924
Kaolin + 6% Lime + 10% Zeolite A	194	371	670	906	1481
Kaolin + 6% Lime + 15% Zeolite A	199	373	875	1028	3288
Kaolin + 6% Lime + 5% Zeolite B	271	251	452	567	982
Kaolin + 6% Lime +10% Zeolite B	193	253	480	628	797
Kaolin + 6% Lime + 15% Zeolite B	181	255	542	617	936

The unconfined compressive strength (UCS) of kaolin-lime with various percentages of zeolite addition at different days of curing period (0, 7, 14, 28 and 56 days) was summarized in Figure 4.4. The sufficient amount of hydrated lime and longer curing period especially after 56 days give a significant effect on UCS. The gain of UCS pattern shows different value with different type of zeolite and it is much dependent on the properties of the zeolite and the mixture reaction. Figure 4.4 shows the strength increases with time but before day 14, the mixture is going through modification process where the flocculation and rearrangement of soil particle provide instability of the mixture. After day 28, the mixture is almost reach the stable condition.

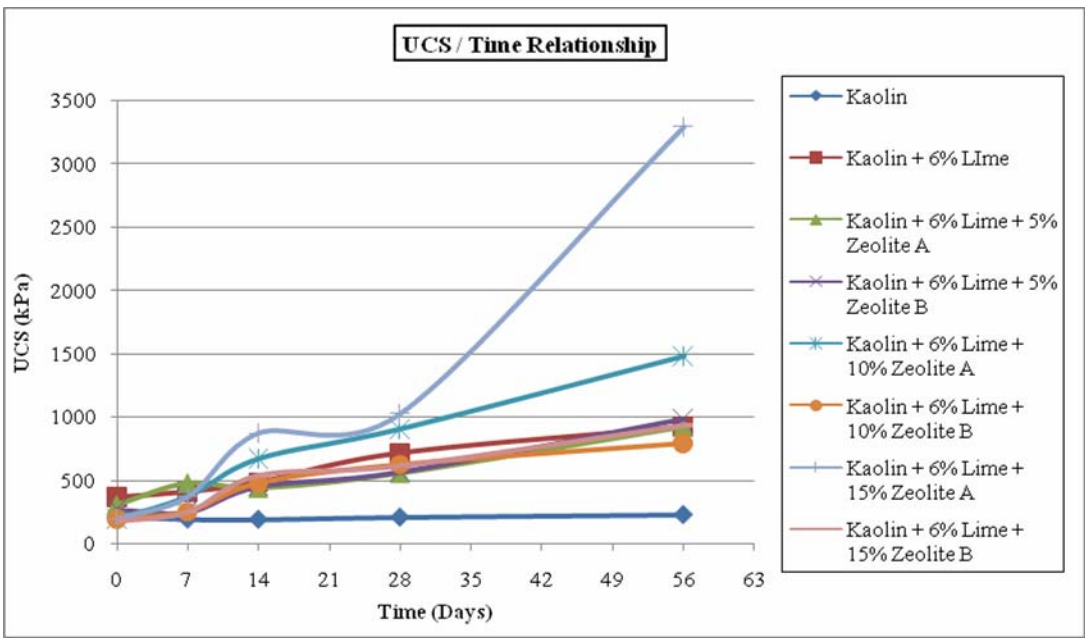

Figure 4.4: Unconfined Compressive Strength Result

Comparing between lime-kaolin mixture with zeolite A and zeolite B, lime-kaolin stabilized with zeolite A yields higher strength than lime-kaolin stabilized with zeolite B. Zeolite A is a stable synthetic zeolite processed by hydrothermal method whereas zeolite B is a natural zeolite that are rarely pure and contaminated into varying degrees of other minerals like metals and quartz. The presence of quartz particularly gives rise to ineffective stabilization with lime. Refer Appendix C for comparison of UCS value for each mixture in varies curing period.

The percentage of strength increases are shown in Figure 4.5, Figure 4.6 and Figure 4.7 for percentage increase in comparison between lime stabilization and lime stabilization with zeolite additive. Form the graphs, it can be conclude that a small addition of zeolite does not effective in improving lime stabilization. This is due to the unsufficient minerals to react and to bond the lime and zeolite minerals. However, when the percentage of zeolite is increase, the strength tends to be higher and it is really effective in enhancing lime stabilization. It required cementations to bridging between the particle and this resulted to higher strength to the mixture.

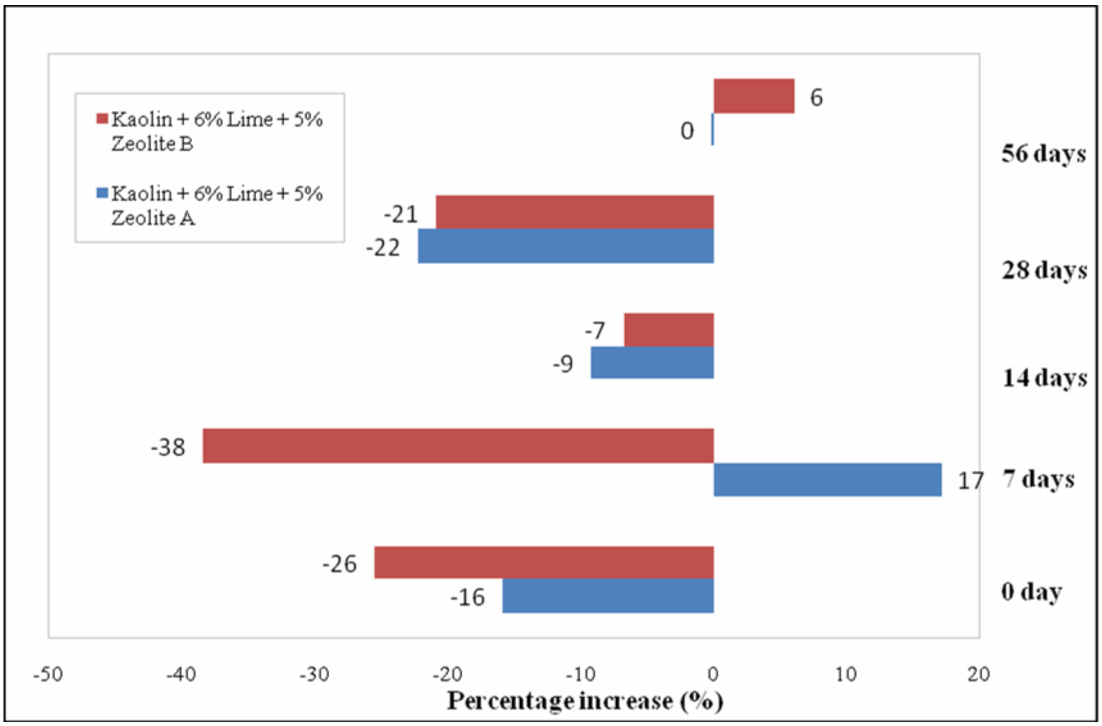

Figure 4.5: Strength percentage increase in soil + 6% lime + 5% zeolite compared with soil + 6% lime stabilization

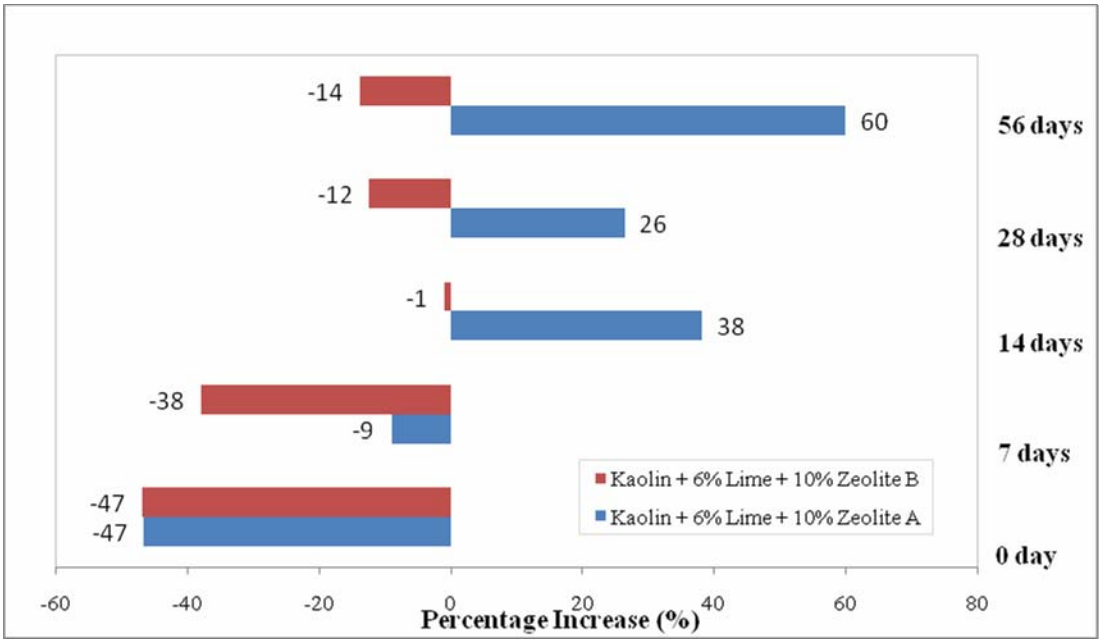

Figure 4.6: Strength percentage increase in soil + 6% lime + 10% zeolite compared with soil + 6% lime stabilization

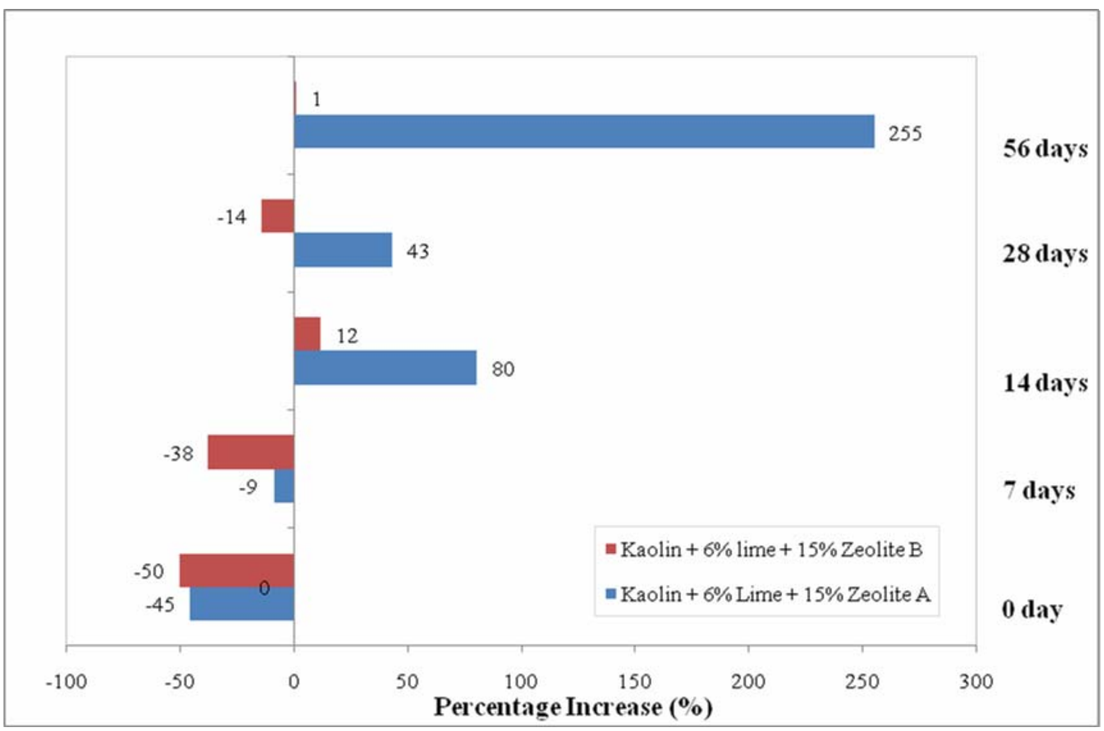

Figure 4.7: Strength percentage increase in soil + 6% lime + 15% zeolite compared with soil + 6% lime stabilization.

CHAPTER 5

CONCLUSION

The physical and geochemistry results of the lime treated and untreated soils were presented. Based on the laboratory results, the following summary has been drawn:

i. Basic physical and geochemistry properties of kaolin such as specific gravity, Atterberg limit, particle size distribution, soil classification, initial consumption of lime (ICL), available lime content (ALC), optimum moisture content (OMC), and maximum dry density (MDD) in this studies were summarized in Appendix A and Appendix B. Based on the results of soil classification test, the soil is classified into fine-grained soil that consists of 81.17% of fine materials. As the amount of clay content more than 10% thus this soil is suitable to be stabilized with lime.

ii. Inspection of the lime quality used in this investigation is essential as it determines the effectiveness of lime modification and stabilization. Standard means of specifying the content of lime should be used. Hydrated lime with the ALC (as CaO) of 64.8% and ALC (as $Ca(OH)_2$) of 85.6% was used in the investigation.

iii. Maximum dry density (MDD) and optimum dry density (OMC) were different between untreated sample and treated sample with lime and various content of zeolite. The reduction in dry density could be due to the flocculation and agglomeration effect of soil particles which reduce compactibility and hence the density of the treated soil. The OMC generally increases with addition of lime and zeolite compared to the unstabilised soil. This is due to the higher consumption of water for the reaction to take place.

iv. The unconfined compressive strength (UCS) of kaolin-lime with various percentages of zeolite addition at different days of curing period were summarized in Appendix C. The determination of optimum moisture content is vital during compaction and prior to the preparation of Unconfined Compression Test. An addition of synthetic zeolite (zeolite A) shows a significant improvement in shear strength with an increase of about 255% compared to lime stabilized soil at an optimum mix of 6%lime +15% zeolite cured after 56 days. Zeolite B however shows no significant improvement. This is due to impurities composition of zeolite B.

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APPENDIX A

RESULT OF SOIL CLASSIFICATION

APPENDIX A1: ATTERBERG LIMIT TEST

i. Liquid Limit Test (Cone Penetration Test)

	Unit	Test no.			
		1	2	3	4
Initial dial gauge reading	mm	0 0 0	0 0 0	0 0 0	0 0 0
Average penetration	mm	16.60	17.30	20.50	22.20
Container no.		A	B	C	D
Mass of wet soil + container	g	32.217	16.45	16.739	17.52
Mass of dry soil + container	g	30.825	14.39	14.533	15.221
Mass of container	g	27.641	9.629	9.472	10.107
Mass of moisture	g	1.39	2.06	2.21	2.30
Mass of dry soil	g	3.18	4.76	5.06	5.11
Moisture Content	%	43.72	43.27	43.59	44.96

LL (moisture content at 20mm penetration) = **44.2%**

ii. Plastic Limit Test

DESCRIPTION	**UNIT**			
Test no.		1	2	3
Container no.		A	B	C
Mass of wet soil + container	g	12.190	29.550	8.471
Mass of dry soil + container	g	11.780	29.219	8.176
Mass of container	g	9.968	27.916	6.904
Mass of moisture	g	0.410	0.331	0.295
Mass of dry soil	g	1.812	1.303	1.272
Moisture Content	%	22.63	25.40	23.19

PL (average) = **23.7%**

APPENDIX A2: PARTICLE SIZE DISTRIBUTION

i. Hydrometer Sidementation

Calibration and Sample Data

DESCRIPTION	SYMBOL	VALUE	UNIT
Hydrometer no.		3328	
Meniscus correction	*C*m	0.5	
Reading in dispersant	*Ro'*	0.5	
Calibration equation H_r = 203.93-3.8345Rh			
Dry mass of soil	*m*	50	g
Particle density measured/assumed *ρs*		2.41	Mg/m^3
Viscosity of water at 27.0 ^oC	*h*	2.41	mPa.s

Pretreatment

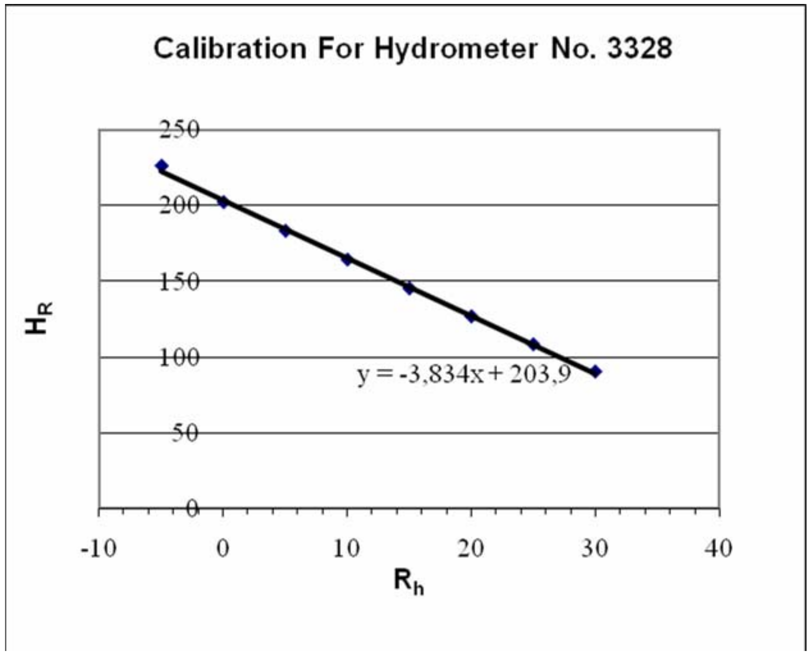
Pretreated with Sodium Hexametaphospate & Sodium Carbonat			
Initial dry mass of sample	m_o	50.00	g
Dry mass after pretreatment	*m*	49.64	g

Pretreatment loss	$m_o - m$	0.36	g
		0.72	%

Calibration for Hydrometer (No.3288)

Mass	=	66.786	g
N	=	9.5	mm
h	=	180	mm
$\mathbf{V_h}$	=	60	ml
L	=	272	mm
H	=	$N+d_1$, $N+d_2$, ...$N+d_7$	

	H	$\mathbf{H_R}$	$\mathbf{R_h}$
$\mathbf{d_0}$	9.5	90.43	30
$\mathbf{d_1}$	27.5	108.43	25
$\mathbf{d_2}$	46.0	126.93	20
$\mathbf{d_3}$	64.5	145.43	15
$\mathbf{d_4}$	83.5	164.43	10
$\mathbf{d_5}$	102.5	183.43	5
$\mathbf{d_6}$	121.5	202.43	0
$\mathbf{d_7}$	145.5	226.43	-5


Calibration For Hydrometer No. 3328
H_R
R_h
y = -3,834x + 203,9
250
200
150
100
50
0
-10
0
10
20
30
40

Test Data

Date	Time 8:45:00 AM	Elapsed Time *t*	Temp *T 8C*	Hydrometer Reading *Rh'*	True Reading *Rh'+Cm = Rh*	Effective Depth *Hr mm*	Modified Reading *Rh' - Ro' = Rd*	*h*	Particle Diameter *D mm*	Percentage finer than D *K (%)*
23.7.2009	8:45:30 AM	0:00:30	26.0	12.50	13.000	154.1	12.0	0.8748	0.076	41.32
23.7.2009	8:46:00 AM	0:01:00	26.0	12.50	13.000	154.1	12.0	0.8748	0.054	41.32
23.7.2009	8:47:00 AM	0:02:00	26.0	12.00	12.500	156.0	11.5	0.8748	0.038	39.60
23.7.2009	8:49:00 AM	0:04:00	26.0	12.00	12.500	156.0	11.5	0.8748	0.027	39.60
23.7.2009	8:53:00 AM	0:08:00	26.0	12.00	12.500	156.0	11.5	0.8748	0.019	39.60
23.7.2009	9:00:00 AM	0:15:00	26.0	10.50	11.000	161.8	10.0	0.8748	0.014	34.43
23.7.2009	9:15:00 AM	0:30:00	26.0	9.50	10.000	165.6	9.0	0.8748	0.010	30.99
23.7.2009	9:45:00 AM	1:00:00	25.5	8.50	9.000	169.4	8.0	0.884325	0.007	27.55
23.7.2009	10:45:00 AM	2:00:00	25.0	7.50	8.000	173.3	7.0	0.8941	0.005	24.10
23.7.2009	12:45:00 PM	4:00:00	24.0	6.00	6.500	179.0	5.5	0.9144	0.004	18.94
23.7.2009	4:45:00 PM	8:00:00	22.5	5.00	5.500	182.8	4.5	0.946725	0.003	15.49
24.7.2009	8:45:00 AM	24:00:00	24.5	2.50	3.000	192.4	2.0	0.904125	0.002	6.89

i. Dry Sieving

Sieve Size (mm)	Mass retained (g)	Percentage retain (%)	Cumulative percentage passing (%)
5.00	0	0.00	100.00
3.35	0	0.00	100.00
2.00	0	0.00	100.00
1.18	0.044	0.98	99.02
0.60	0.121	2.69	96.33
0.425	0.051	1.14	95.20
0.300	0.076	1.69	93.51
0.212	0.109	2.43	91.09
0.150	0.189	4.20	86.89
0.063	0.256	5.70	81.17

Passing 0.063	3.645	81.16	0.01

Sieve Size (mm)	Mass passing (%)	Classification
2.00	100.00	
0.425	95.20	Gravel = 4.80
0.063	81.17	Sand = 14.03
0.002	11	Silt / Clay = 81.17
		Silt = 70.17
		Clay = 11.00

APPENDIX B

RESULT OF COMPACTION TEST

APPENDIX B1: COMPACTION TESTS RESULT (PART I – DATA TABLES)

i. **Kaolin**

DESCRIPTION	UNIT	VALUES			
Percentage of water addition	%	14%	17%	20%	23%
Mass of the empty mould	kg	3.75	3.681	3.698	3.679
Mass of the empty mould + wet	kg	5.534	5.605	5.665	5.543

soil					
Mass of wet soil	kg	1.784	1.924	1.967	1.864
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.784	1.924	1.967	1.864
Dry Density	Mg/m^3	1.550	1.580	1.579	1.451
Mass of the empty container	g	9.767	9.802	9.595	9.386
Mass of the empty cont. + wet soil	g	28.828	27.153	37.151	37.494
Mass of the empty cont. + dry soil	g	26.325	24.049	31.71	31.269
Mass of wet soil	g	2.503	3.104	5.441	6.225
Mass of dry soil	g	16.558	14.247	22.115	21.883
Moisture content	%	15.1	21.8	24.6	28.4
Specific Gravity	2.56				
Air Void Content:	Mg/m^3				
0%	Mg/m^3	1.846	1.643	1.571	1.481
5%	Mg/m^3	1.753	1.561	1.492	1.407
10%	Mg/m^3	1.661	1.479	1.414	1.333

ii. Kaolin + 6% Lime

DESCRIPTION	UNIT	VALUES				
Percentage of water addition	%	17%	23%	27%	32%	35%
Mass of the empty mould	kg	3.436	3.303	3.33	3.33	3.66
Mass of the empty mould + wet soil	kg	5.166	5.206	5.238	5.166	5.382

Mass of wet soil	kg	1.73	1.903	1.908	1.836	1.722
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.73	1.903	1.908	1.836	1.722
Dry Density	Mg/m^3	1.478	1.555	1.511	1.393	1.282
Mass of the empty container	g	9.822	9.538	10.258	9.73	6.94
Mass of the empty cont. + wet soil	g	46.784	40.777	50.998	53.679	78.715
Mass of the empty cont. + dry soil	g	41.4	35.072	42.524	43.067	60.356
Mass of wet soil	g	5.384	5.705	8.474	10.612	18.359
Mass of dry soil	g	31.578	25.534	32.266	33.337	53.416
Moisture content	%	17.0	22.3	26.3	31.8	34.4
Specific Gravity	2.56					
Air Void Content	Mg/m^3					
0%	Mg/m^3	1.782	1.629	1.531	1.411	1.362
5%	Mg/m^3	1.693	1.547	1.454	1.340	1.294
10%	Mg/m^3	1.604	1.466	1.378	1.269	1.226

iii. Kaolin + 6% Lime + 5% Zeolite A

DESCRIPTION	UNIT	VALUES				
Percentage of water addition	%	14%	17%	23%	27%	32%
Mass of the empty mould	kg	3.309	3.728	3.728	3.745	3.745

Mass of the empty mould + wet soil	kg	4.931	5.441	5.623	5.65	5.578
Mass of wet soil	kg	1.622	1.713	1.895	1.905	1.833
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.622	1.713	1.895	1.905	1.833
Dry Density	Mg/m^3	1.424	1.471	1.540	1.517	1.402
Mass of the empty container	g	6.927	6.947	27.812	6.797	7.014
Mass of the empty cont. + wet soil	g	47.864	37.547	57.147	30.813	39.298
Mass of the empty cont. + dry soil	g	42.862	33.23	51.657	25.92	31.709
Mass of wet soil	g	5.002	4.317	5.49	4.893	7.589
Mass of dry soil	g	35.935	26.283	23.845	19.123	24.695
Moisture content	%	13.9	16.4	23.0	25.6	30.7
Specific Gravity	2.56					
Air Void Content	Mg/m^3					
0%	Mg/m^3	1.887	1.802	1.611	1.547	1.433
5%	Mg/m^3	1.793	1.712	1.530	1.469	1.361
10%	Mg/m^3	1.699	1.622	1.450	1.392	1.290

iv. Kaolin +6% Lime + 10% Zeolite A

DESCRIPTION	UNIT	VALUES

Percentage of water addition	%	14%	17%	23%	27%	32%	35%
Mass of the empty mould	kg	3.251	3.707	3.309	3.746	3.33	3.659
Mass of the empty mould + wet soil	kg	4.867	5.41	5.116	5.618	5.155	5.386
Mass of wet soil	kg	1.616	1.703	1.807	1.872	1.825	1.727
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.616	1.703	1.807	1.872	1.825	1.727
Dry Density	Mg/m^3	1.415	1.452	1.474	1.491	1.404	1.290
Mass of the empty container	g	10.201	6.537	9.07	18.435	18.417	9.5586
Mass of the empty cont. + wet soil	g	34.381	35.637	57.049	55.64	51.508	55.358
Mass of the empty cont. + dry soil	g	31.371	31.351	48.2	48.06	43.876	43.762
Mass of wet soil	g	3.01	4.286	8.849	7.58	7.632	11.596
Mass of dry soil	g	21.17	24.814	39.13	29.625	25.459	34.2034
Moisture content	%	14.2	17.3	22.6	25.6	30.0	33.9
Specific Gravity	2.56						
Air Void Content	Mg/m^3						
0%	Mg/m^3	1.877	1.775	1.621	1.547	1.448	1.371
5%	Mg/m^3	1.783	1.686	1.540	1.469	1.376	1.302
10%	Mg/m^3	1.689	1.598	1.459	1.392	1.304	1.233

v. Kaolin + 6% Lime + 15% Zeolite A

DESCRIPTION	UNIT	VALUES			
Percentage of water addition	%	17%	23%	27%	32%
Mass of the empty mould	kg	3.658	3.33	3.33	3.66
Mass of the empty mould + wet soil	kg	5.265	5.094	5.206	5.416
Mass of wet soil	kg	1.607	1.764	1.876	1.756
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.607	1.764	1.876	1.756
Dry Density	Mg/m^3	1.367	1.449	1.489	1.336
Mass of the empty container	g	6.704	10.239	6.786	9.451
Mass of the empty cont. + wet soil	g	37.978	40.059	36.361	47.189
Mass of the empty cont. + dry soil	g	33.309	34.739	30.267	38.158
Mass of wet soil	g	4.669	5.32	6.094	9.031
Mass of dry soil	g	26.605	24.5	23.481	28.707
Moisture content	%	17.5	21.7	26.0	31.5
Specific Gravity	2.56				
Air Void Content	Mg/m^3				
0%	Mg/m^3	1.766	1.645	1.538	1.418
5%	Mg/m^3	1.678	1.563	1.461	1.347
10%	Mg/m^3	1.590	1.481	1.384	1.276

vi. Kaolin + 6% Lime + 5% Zeolite B

DESCRIPTION	UNIT	VALUES				
Percentage of water addition	%	17%	23%	27%	32%	35%
Mass of the empty mould	kg	3.252	3.762	3.659	3.436	3.659
Mass of the empty mould + wet soil	kg	4.99	5.63	5.493	5.283	5.389
Mass of wet soil	kg	1.738	1.868	1.834	1.847	1.73
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.738	1.868	1.834	1.847	1.73
Dry Density	Mg/m^3	1.477	1.516	1.444	1.413	1.282
Mass of the empty container	g	6.804	10.294	9.671	9.393	6.758
Mass of the empty cont. + wet soil	g	40.301	38.752	55.816	51.726	48.501
Mass of the empty cont. + dry soil	g	35.263	33.391	46.015	41.787	37.701
Mass of wet soil	g	5.038	5.361	9.801	9.939	10.8
Mass of dry soil	g	28.459	23.097	36.344	32.394	30.943
Moisture content	%	17.7	23.2	27.0	30.7	34.9
Specific Gravity	2.56					
Air Void Content	Mg/m^3					
0%	Mg/m^3	1.762	1.606	1.514	1.434	1.352
5%	Mg/m^3	1.674	1.526	1.439	1.362	1.284

	10%	Mg/m^3	1.585	1.445	1.363	1.290	1.217

vii. Kaolin + 6% Lime + 10% Zeolite B

DESCRIPTION	UNIT	VALUES				
Percentage of water addition	%	17%	23%	27%	32%	35%
Mass of the empty mould	kg	3.707	3.667	3.762	3.436	3.211
Mass of the empty mould + wet soil	kg	5.352	5.442	5.628	5.278	5.007
Mass of wet soil	kg	1.645	1.775	1.866	1.842	1.796
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.645	1.775	1.866	1.842	1.796
Dry Density	Mg/m^3	1.411	1.448	1.501	1.487	1.350
Mass of the empty container	g	9.503	10.289	9.122	5.622	9.625
Mass of the empty cont. + wet soil	g	29.143	38.431	34.107	33.007	32.549
Mass of the empty cont. + dry soil	g	26.355	33.243	29.223	27.726	26.856
Mass of wet soil	g	2.788	5.188	4.884	5.281	5.693

Mass of dry soil		g	16.852	22.954	20.101	22.104	17.231
Moisture content		%	16.5	22.6	24.3	23.9	33.0
Specific Gravity		2.56					
Air Void Content		Mg/m^3					
	0%	Mg/m^3	1.798	1.622	1.578	1.588	1.387
	5%	Mg/m^3	1.708	1.541	1.499	1.509	1.318
	10%	Mg/m^3	1.619	1.460	1.420	1.430	1.248

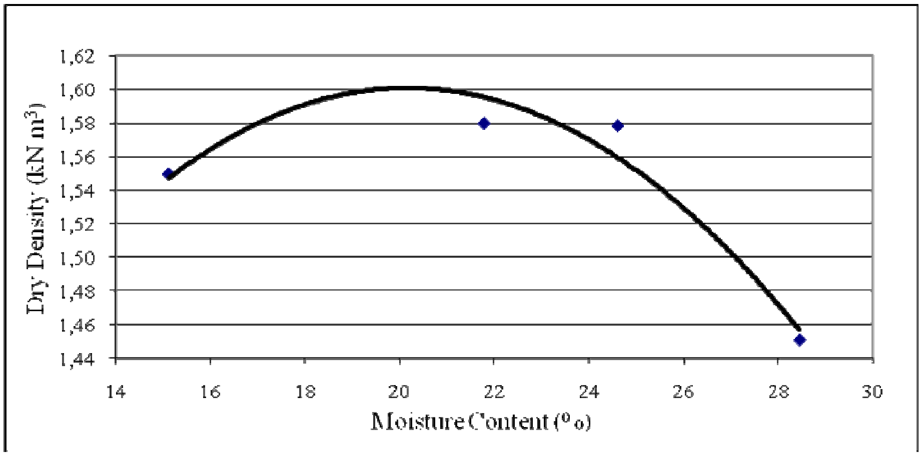
viii. Kaolin + 6% Lime + 15% Zeolite B

DESCRIPTION	UNIT	VALUES				
Percentage of water addition	%	17%	23%	27%	32%	35%
Mass of the empty mould	kg	3.251	3.762	3.436	3.668	3.707
Mass of the empty mould + wet soil	kg	4.9	5.561	5.333	5.448	5.505
Mass of wet soil	kg	1.649	1.799	1.897	1.78	1.798
Volume of the mould, V	m^3	0.001	0.001	0.001	0.001	0.001
Bulk Density	Mg/m^3	1.649	1.799	1.897	1.78	1.798
Dry Density	Mg/m^3	1.421	1.471	1.518	1.364	1.335

Mass of the empty container	g	9.935	7.002	9.803	9.352	9.505
Mass of the empty cont. + wet soil	g	28.442	32.325	41.682	40.125	47.466
Mass of the empty cont. + dry soil	g	25.879	27.713	35.312	32.926	37.685
Mass of wet soil	g	2.563	4.612	6.37	7.199	9.781
Mass of dry soil	g	15.944	20.711	25.509	23.574	28.18
Moisture content	%	16.1	22.3	25.0	30.5	34.7
Specific Gravity	2.56					
Air Void Content	Mg/m^3					
0%	Mg/m^3	1.814	1.631	1.562	1.437	1.356
5%	Mg/m^3	1.723	1.549	1.484	1.365	1.288
10%	Mg/m^3	1.632	1.467	1.406	1.293	1.220

APPENDIX B2: COMPACTION TESTS RESULT (PART II – GRAPH PLOT)

i. Compaction Curve for Kaolin

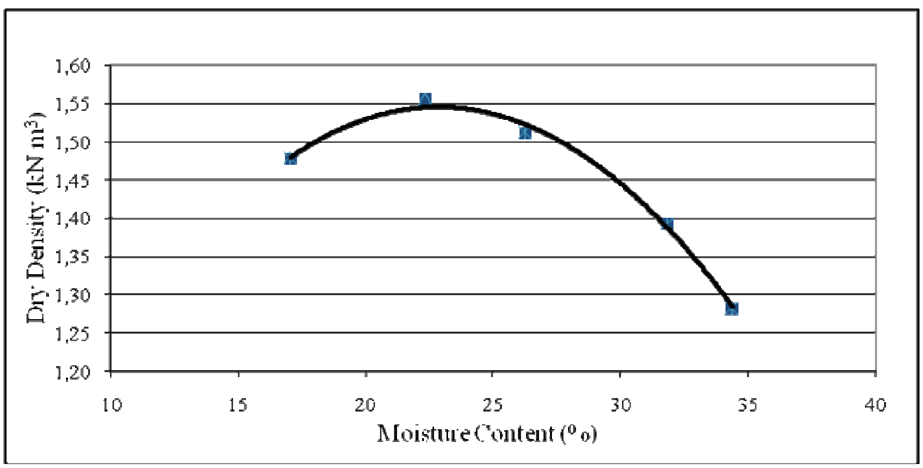


From the graph:

MDD = 1.600

OMC = 20.0

ii. Compaction Curve for Kaolin + 6% Lime

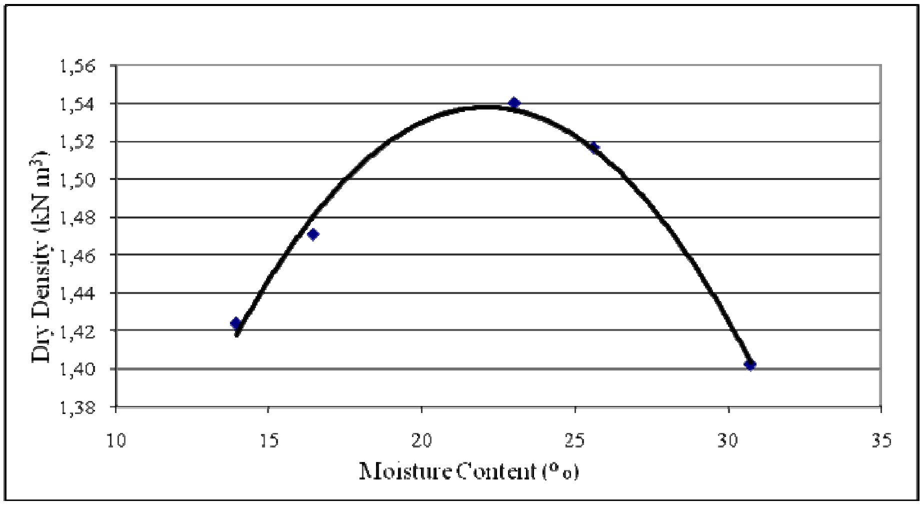


From the graph:

MDD = 1.545

OMC = 22.7

iii. Compaction Curve for Kaolin + 6% Lime + 5% Zeolite A

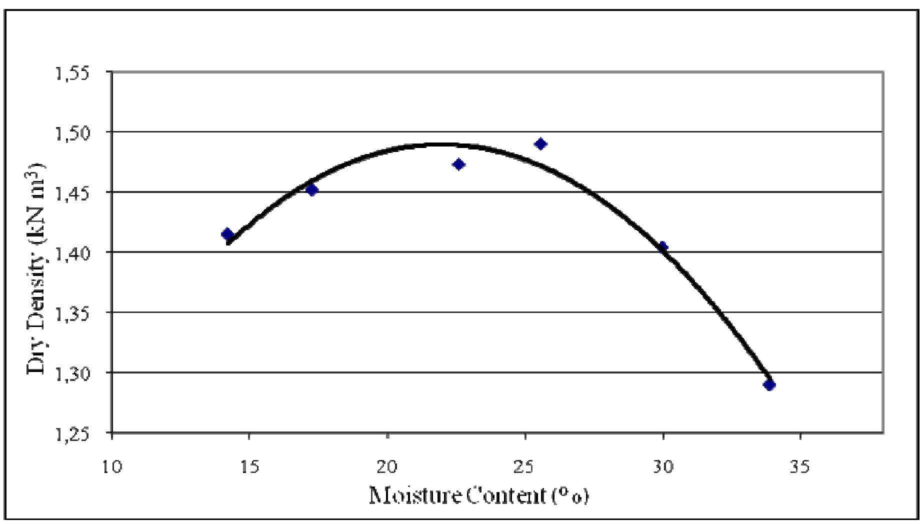


From the graph:

MDD = 1.583

OMC = 22.0

iv. Compaction Curve for Kaolin + 6% Lime + 10% Zeolite A

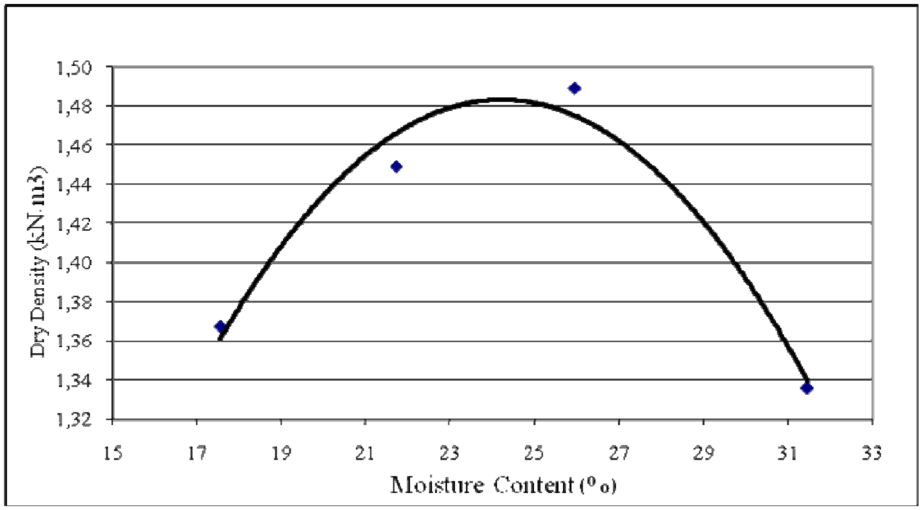


From the graph:

MDD = 1.490

OMC = 21.6

v. Compaction Curve for Kaolin + 6% Lime + 15% Zeolite A

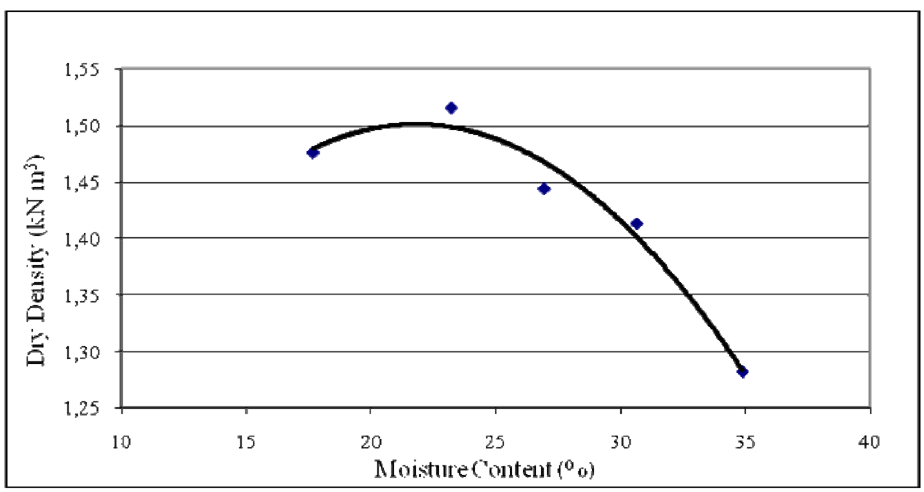


From the graph:

MDD = 1.482

OMC = 24.3

vi. Compaction Curve for Kaolin + 6% Lime + 5% Zeolite B

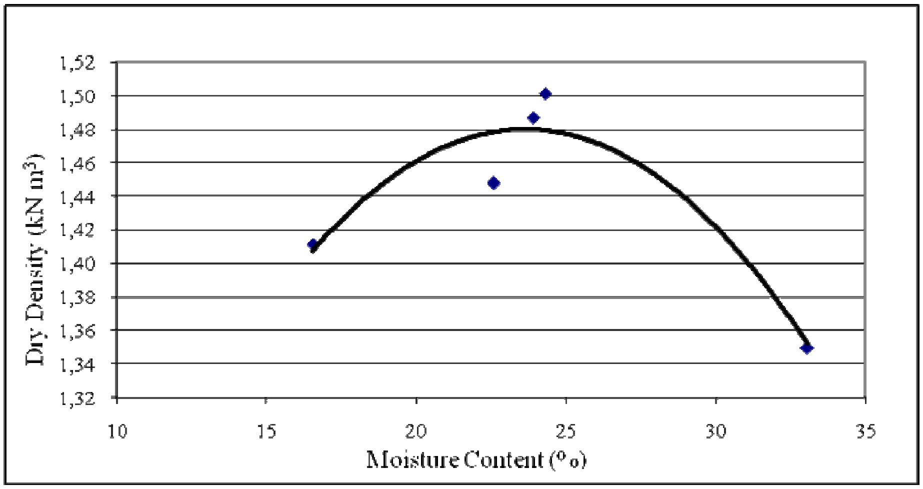


From the graph:

MDD = 1.502

OMC = 21.9

vii. Compaction Curve for Kaolin + 6% Lime + 10% Zeolite B

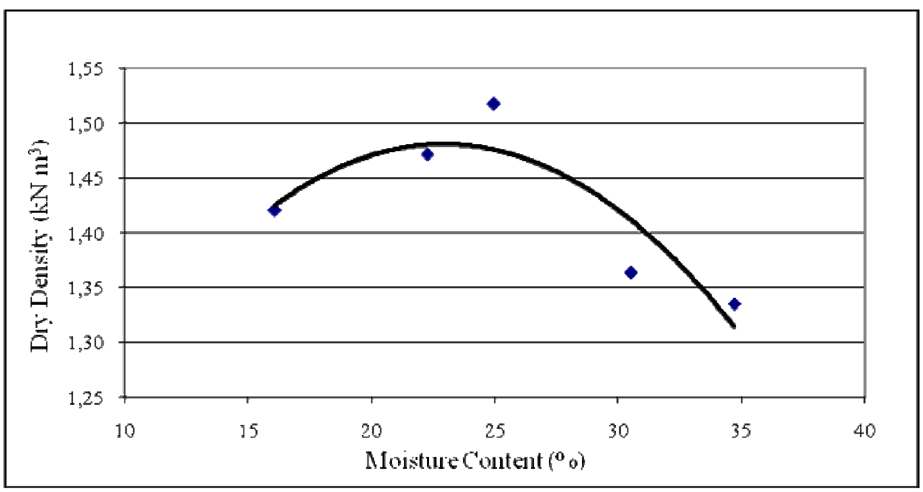


From the graph:

MDD = 1.480

OMC = 23.3

viii. Compaction Curve for Kaolin + 6% Lime + 15% Zeolite B



From the graph:

MDD = 1.480

OMC = 22.7

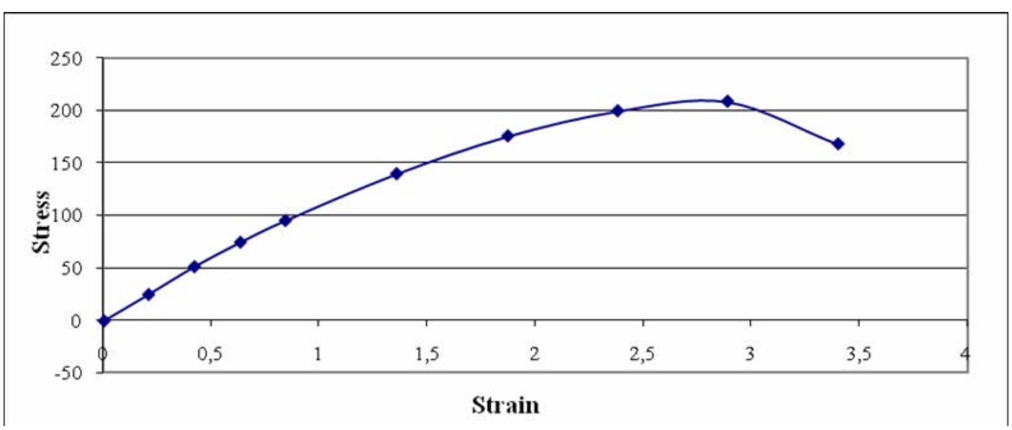
APPENDIX C

RESULT OF UNCONFINED COMPRESSION TEST

APPENDIX C1: UNCONFINED COMPRESSION STRENGTH (0 DAY)

i. Untreated Soil (Kaolin)

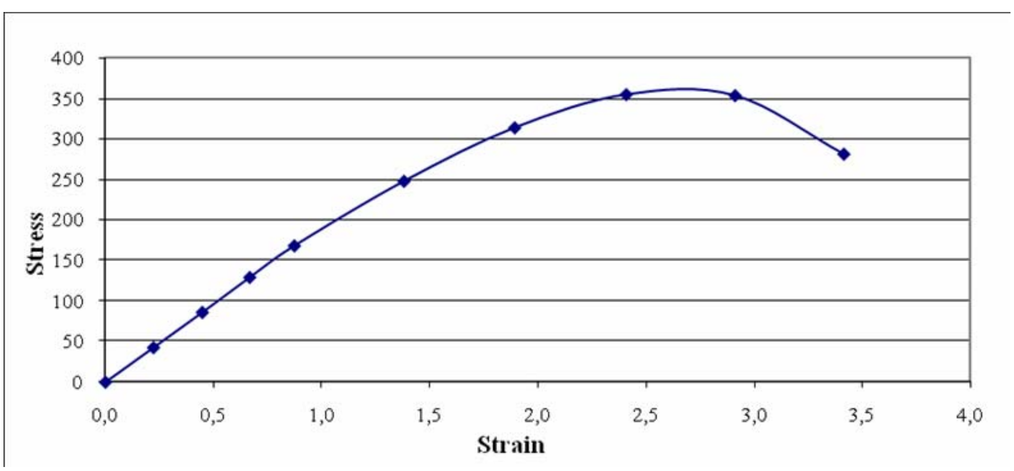
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	1.47059	0.0039	0.74897
0.2098	47.9412	0.2098	24.4163
0.4221	100.0001	0.4221	50.9296
0.6345	145.5884	0.6345	74.1476
0.8430	186.1767	0.8430	94.8190
1.3578	273.5297	1.3578	139.3076
1.8726	344.1181	1.8726	175.2579
2.3810	391.1769	2.3810	199.2248
2.8893	408.8240	2.8893	208.2124
3.4016	329.4122	3.4016	167.7682



UCS = 215 kPa

ii. Kaolin + 6% Lime

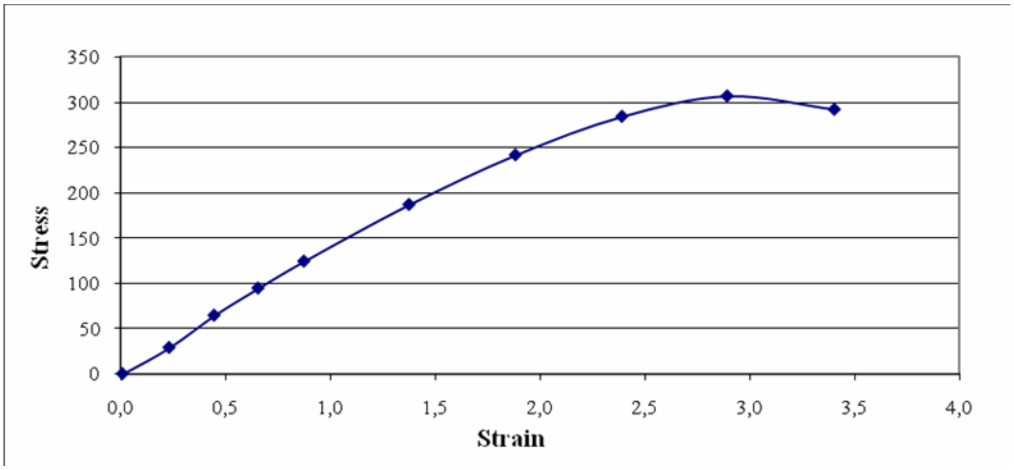
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.00387	0	0.0039	0
0.2256	83.8236	0.2256	42.6910
0.4512	169.1179	0.4512	86.1310
0.6703	253.8238	0.6703	129.2714
0.8765	330.2945	0.8765	168.2176
1.3831	486.7653	1.3831	247.9075
1.8948	616.1772	1.8948	313.8165
2.4104	696.4714	2.4104	354.7100
2.9131	694.1185	2.9131	353.5116
3.4159	552.3536	3.4159	281.3114



UCS = 364 kPa

iii. Kaolin + 6% Lime + 5% Zeolite A

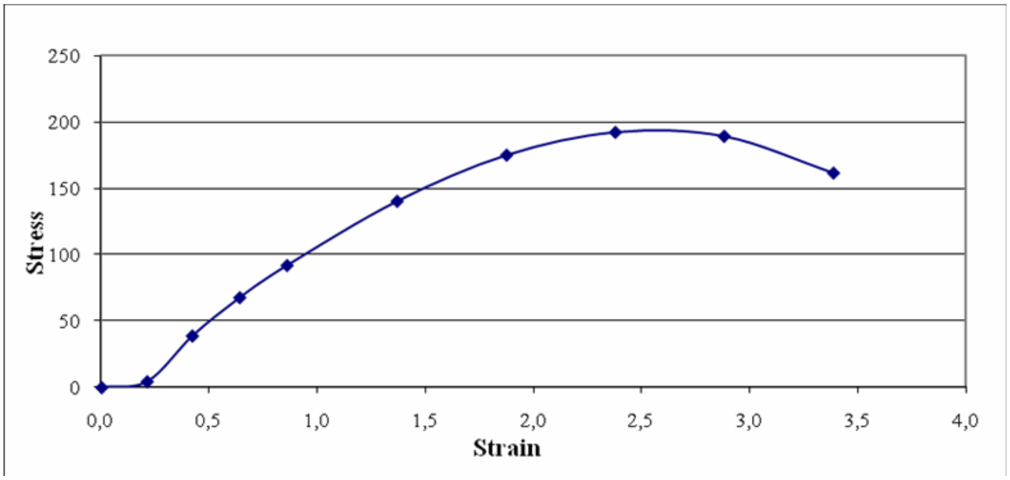
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0064	0	0.0064	0
0.2291	56.7648	0.2291	28.9101
0.4440	126.4707	0.4440	64.4110
0.6538	185.2943	0.6538	94.3696
0.8726	243.5297	0.8726	124.0287
1.3745	366.1769	1.3745	186.4924
1.8829	473.5300	1.8829	241.1668
2.3912	556.7654	2.3912	283.5583
2.8937	600.8831	2.8937	306.0272
3.4054	572.0595	3.4054	291.3475



UCS = 306 kPa

iv. Kaolin + 6% Lime + 10% Zeolite A

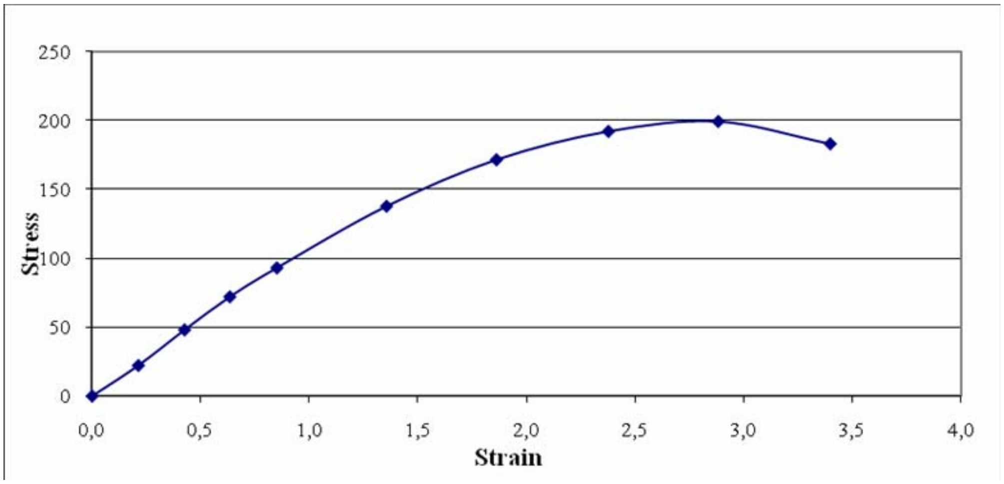
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0064	0	0.0064	0
0.2162	8.8235	0.2162	4.4938
0.4247	76.4707	0.4247	38.9462
0.6435	133.2355	0.6435	67.8563
0.8623	180.8826	0.8623	92.1227
1.3707	275.8827	1.3707	140.5059
1.8764	344.1181	1.8764	175.2579
2.3786	377.9416	2.3786	192.4841
2.8813	372.0593	2.8813	189.4882
3.3866	317.6474	3.3866	161.7765



UCS = 194 kPa

v. **Kaolin + 6% Lime + 15% Zeolite A**

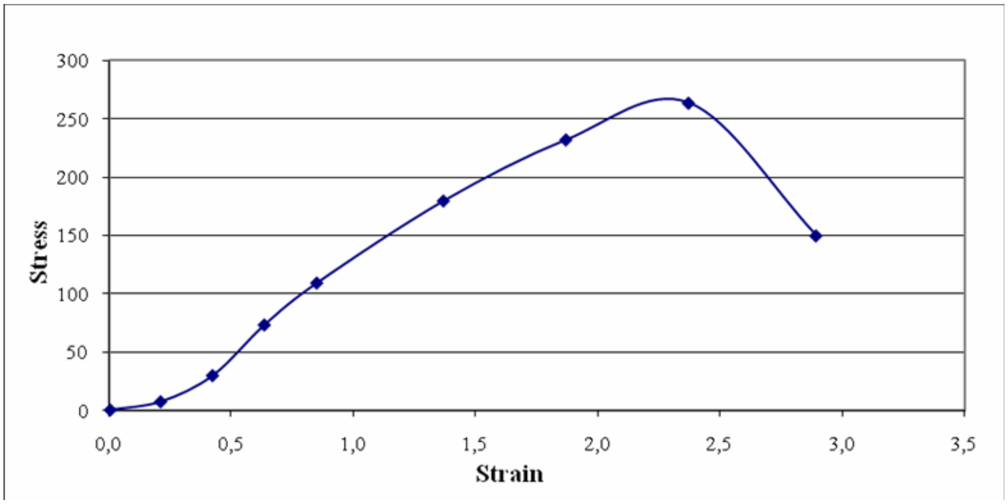
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2162	43.5295	0.2162	22.1694
0.4286	94.1178	0.4286	47.9338
0.6371	141.1766	0.6371	71.9007
0.8533	182.3532	0.8533	92.8717
1.3578	270.0003	1.3578	137.5100
1.8636	336.1769	1.8636	171.2135
2.3784	376.4710	2.3784	191.7351
2.8837	390.5887	2.88373	198.9252
3.3993	358.8240	3.3993	182.7475



UCS = 199 kPa

vi. Kaolin + 6% Lime + 5% Zeolite B

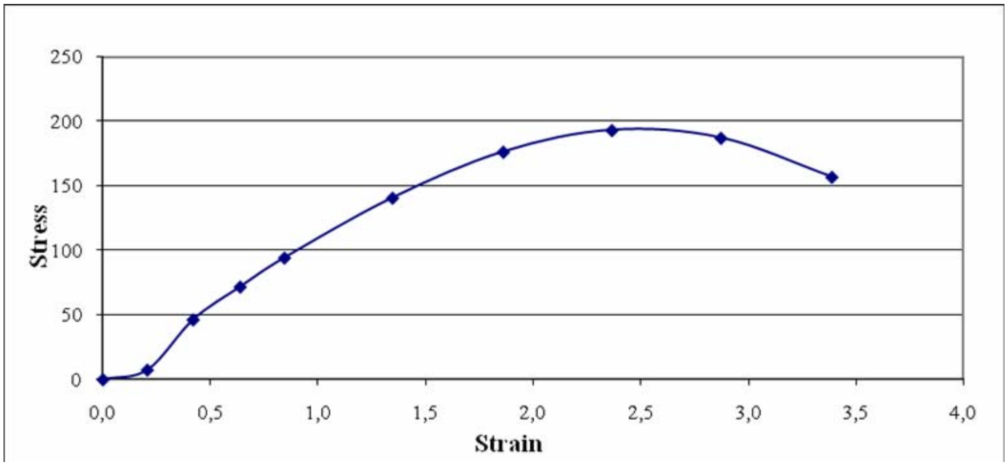
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0.8824	0.0039	0.4494
0.2098	14.7059	0.2098	7.4897
0.4221	58.8236	0.4221	29.9586
0.6345	144.1178	0.6345	73.3986
0.8494	214.7061	0.8494	109.3489
1.3681	352.9416	1.3681	179.7517
1.8700	455.8829	1.8700	232.1793
2.3719	517.6477	2.3719	263.6358
2.8938	294.1180	2.8938	149.7931



UCS = 271 kPa

vii. Kaolin + 6% Lime + 10% Zeolite B

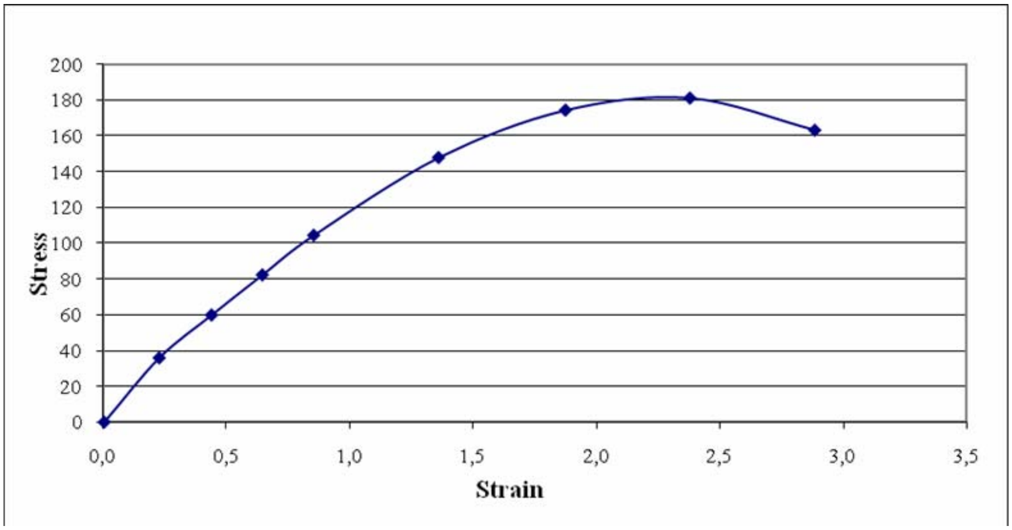
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2098	14.7059	0.2098	7.4897
0.4221	91.1766	0.4221	46.4359
0.6409	141.1766	0.6409	71.9007
0.8468	185.2943	0.8468	94.3696
1.3488	276.4709	1.3488	140.8055
1.8636	346.4710	1.8636	176.4562
2.3681	379.4122	2.3681	193.2331
2.8746	367.6475	2.8746	187.2413
3.3902	308.2357	3.3902	156.9831



UCS = 193 kPa

viii. Kaolin + 6% Lime + 15% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0064	0	0.0064	0
0.2291	70.5883	0.2291	35.9503
0.4414	117.6472	0.4414	59.9172
0.6474	161.7649	0.6474	82.3862
0.8559	205.2944	0.8559	104.5556
1.3616	290.5886	1.3616	147.9956
1.8764	342.6475	1.8764	174.5089
2.3810	355.8828	2.3810	181.2496
2.8874	320.5886	2.8874	163.2744



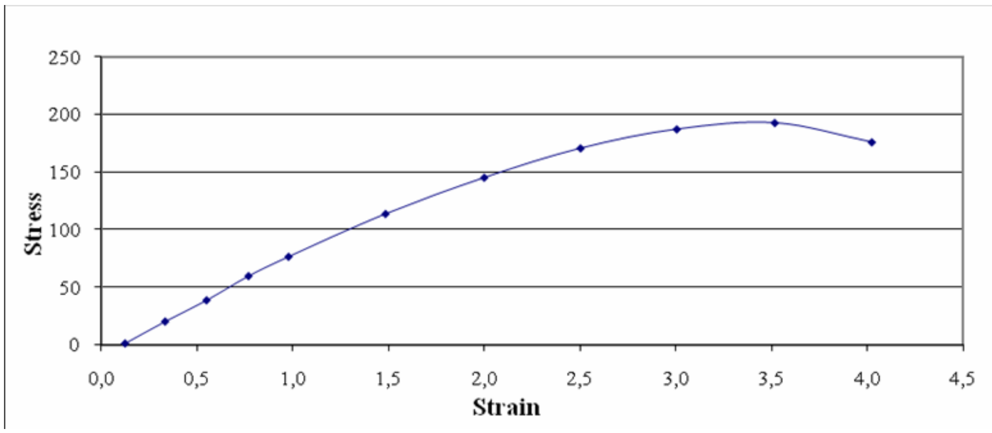
UCS = 181 kPa

APPENDIX C2: UNCONFINED COMPRESSION STRENGTH (7 DAYS)

i. Untreated Soil (Kaolin)

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.1263	2.3529	0.1263	1.1983
0.3351	39.7059	0.3351	20.2221
0.5517	75.8824	0.5517	38.6466
0.7708	117.0590	0.7708	59.6176
0.9796	150.0002	0.9796	76.3945
1.4862	222.9414	1.4862	113.5431
2.0018	284.7062	2.0018	144.9997

2.5045	334.7063	2.5045	170.4645
3.0072	367.0593	3.0072	186.9417
3.5190	377.9416	3.5190	192.4841
4.0255	345.0004	4.0255	175.7073

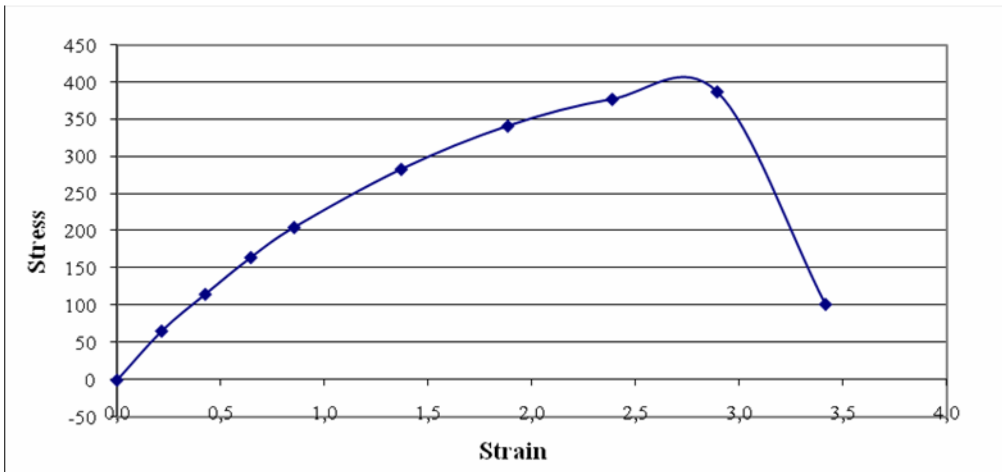


UCS = 192 kPa

ii. Kaolin + 6% Lime

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	-0.8824	0.0039	-0.4494
0.2191	128.8237	0.2191	65.6094
0.4292	225.8826	0.4292	115.0411
0.6484	322.9416	0.6484	164.4728
0.8572	402.3534	0.8572	204.9169
1.3728	555.8830	1.3728	283.1089
1.8858	670.0008	1.8858	341.2286

2.3885	740.5891	2.3885	377.1789
2.8938	760.2950	2.8938	387.2151
3.4159	199.4120	3.4159	101.5597

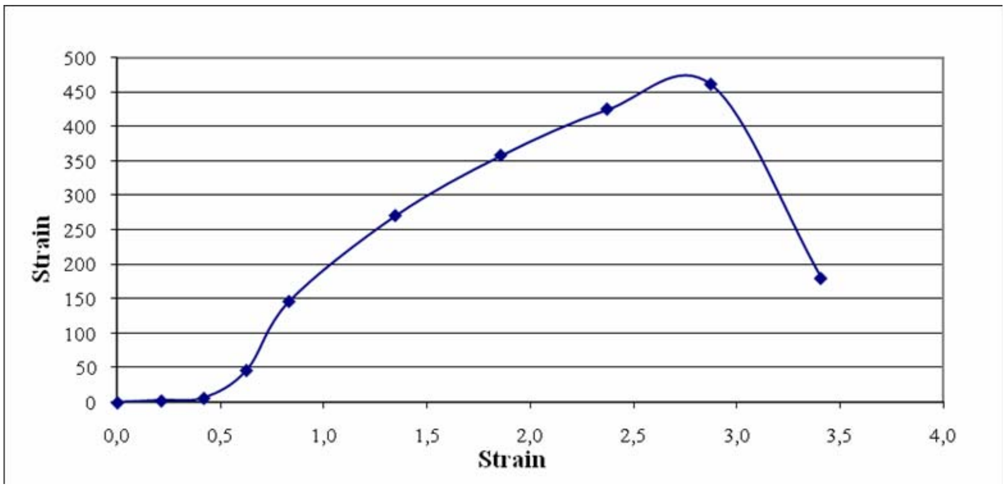


UCS = 408 kPa

iii. Kaolin + 6% Lime + 5% Zeolite A

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2162	5.2941	0.2162	2.6963
0.4221	12.6471	0.4221	6.4411
0.6281	92.0589	0.6281	46.8852
0.8340	288.2356	0.8340	146.7972
1.3488	532.3536	1.3488	271.1255
1.8597	703.8244	1.8597	358.4548

2.3745	835.2951	2.3745	425.4123
2.8769	905.8834	2.8769	461.3626
3.4093	353.8240	3.4093	180.2011

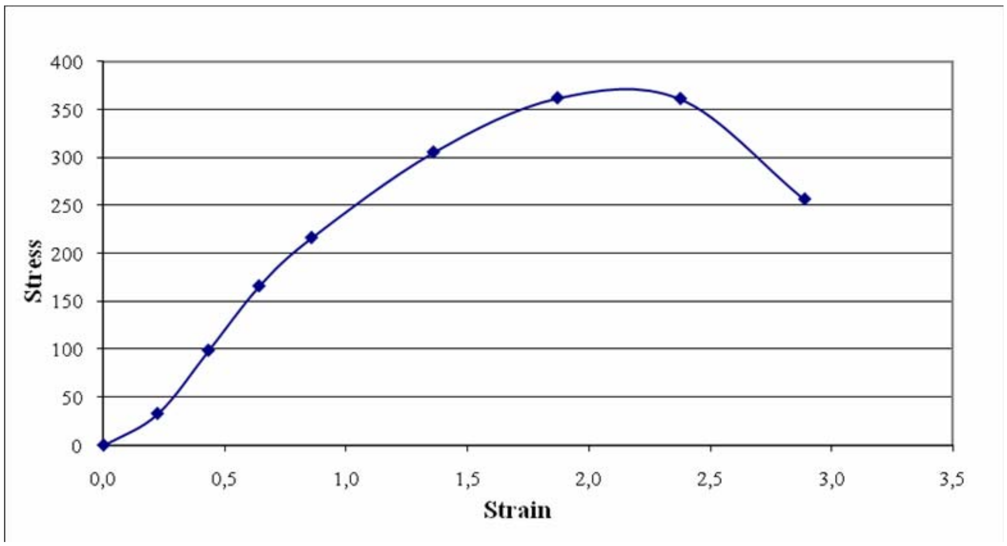


UCS = 478 kPa

iv. Kaolin + 6% Lime + 10% Zeolite A

Axial Displacement, Δ L (mm)	**Compressive Load, P (kN x 10e-3)**	**Strain**	**Stress**
0.0039	0	0.0039	0
0.2252	64.7060	0.2252	32.9545
0.4350	194.1179	0.4350	98.8634
0.6435	325.8827	0.6435	165.9707
0.8597	425.0005	0.8597	216.4510
1.3616	600.0007	1.3616	305.5779

1.8726	711.1773	1.8726	362.1996
2.3790	709.7067	2.3790	361.4507
2.8907	503.8241	2.8907	256.5955

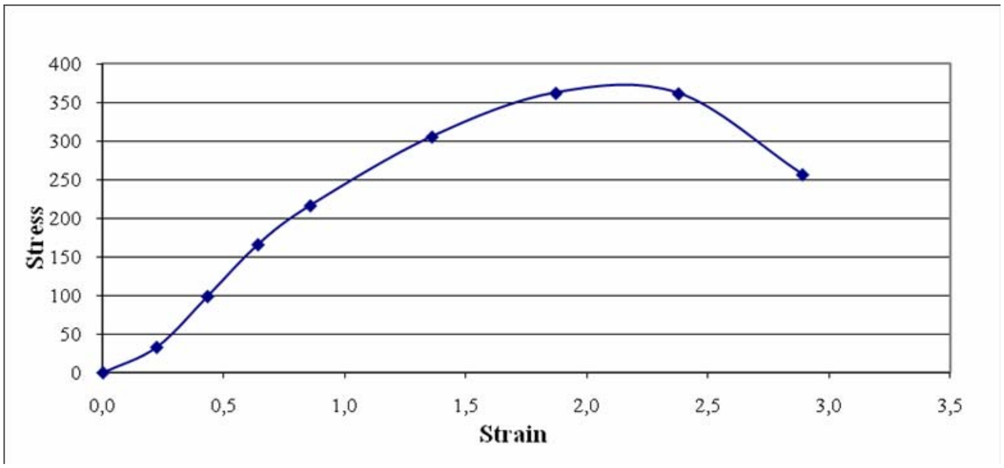


UCS = 371 kPa

v. Kaolin + 6% Lime + 15% Zeolite A

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2252	64.7060	0.2252	32.9545
0.4350	194.1179	0.4350	98.8634
0.6435	325.8827	0.6435	165.9707
0.8597	425.0005	0.8597	216.4510

1.3616	600.0007	1.3616	305.5779
1.8726	711.1773	1.8726	362.1996
2.3790	709.7067	2.3790	361.4507
2.8907	503.8241	2.8907	256.5955

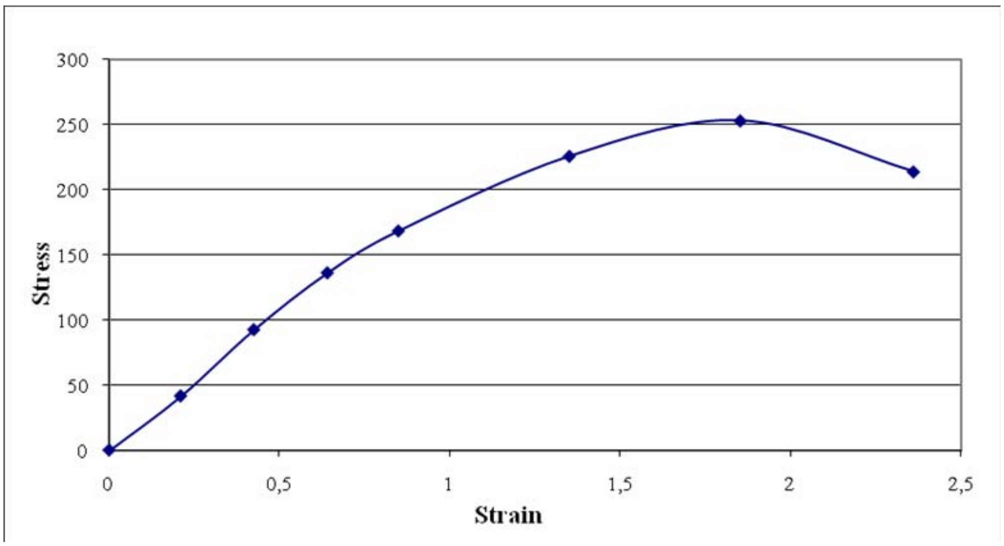


UCS = 373 kPa

vi. Kaolin + 6% Lime + 5% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	0	0
0.2098	81.7648	0.2098	41.6425
0.4247	181.7649	0.4247	92.5721

0.6409	267.6474	0.6409	136.3117
0.8494	330.8828	0.8494	168.5172
1.3514	443.5299	1.3514	225.8879
1.8533	497.0594	1.8533	253.1503
2.3621	420.0005	2.3621	213.9045

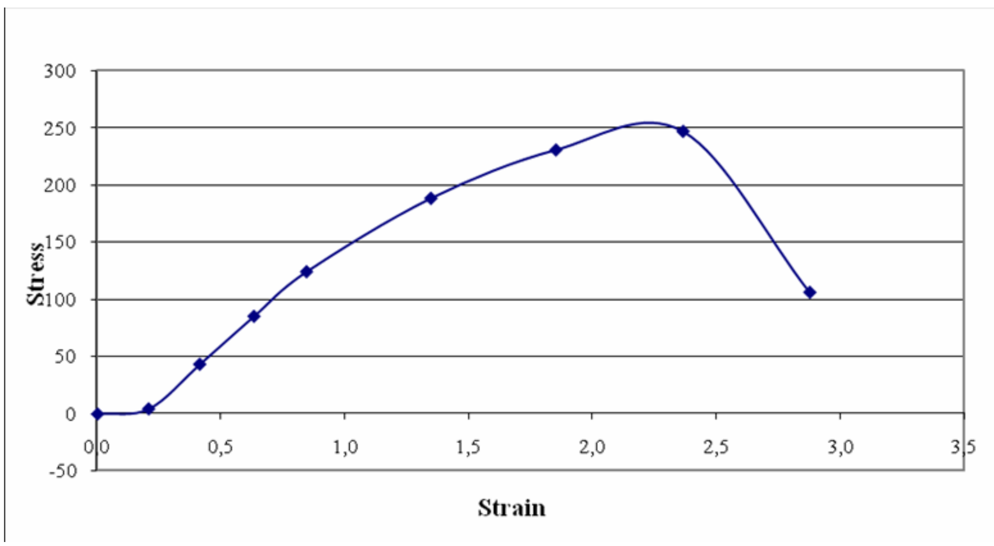


UCS = 251 kPa

vii. Kaolin + 6% Lime + 10% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2098	8.8235	0.2098	4.4938

0.4157	85.2942	0.4157	43.4400
0.6345	167.6473	0.6345	85.3820
0.8468	244.1179	0.8468	124.3282
1.3488	370.0004	1.3488	188.4397
1.8534	452.9417	1.8534	230.6813
2.3664	484.7065	2.3664	246.8590
2.8781	208.8238	2.8781	106.3531

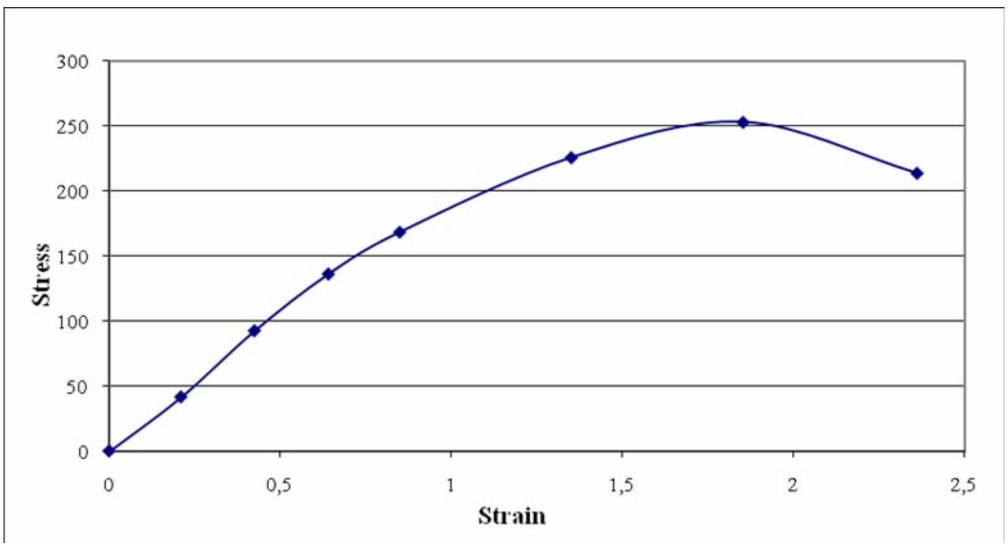


UCS = 253 kPa

viii. Kaolin + 6% Lime + 15% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	0	0

0.2098	81.7648	0.2098	41.6425
0.4247	181.7649	0.4247	92.5721
0.6409	267.6474	0.6409	136.3117
0.8494	330.8828	0.8494	168.5172
1.3514	443.5299	1.3514	225.8879
1.8533	497.0594	1.8533	253.1503
2.3621	420.0005	2.3621	213.9045



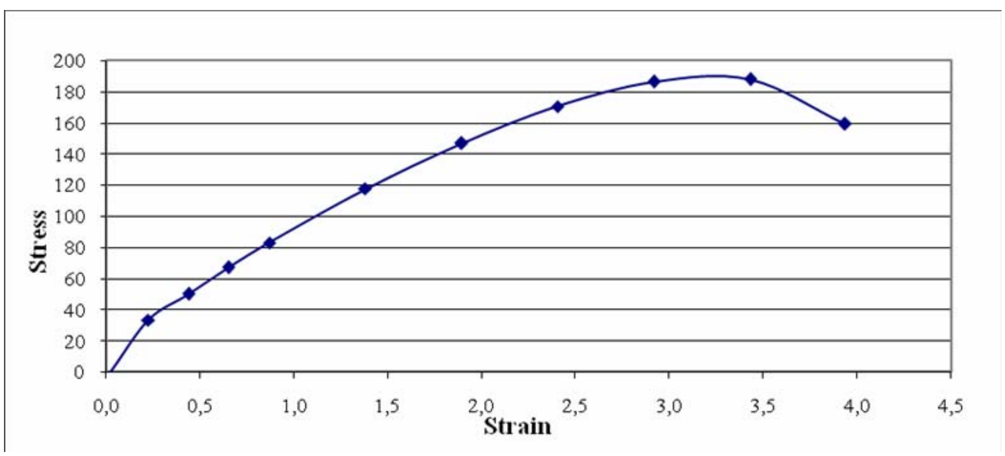
UCS = 255 kPa

APPENDIX C3: UNCONFINED COMPRESSION STRENGTH (14 DAYS)

i. Untreated Soil (Kaolin)

Axial Displacement, Δ L	Compressive Load, P (kN x 10e-	Strain	Stress

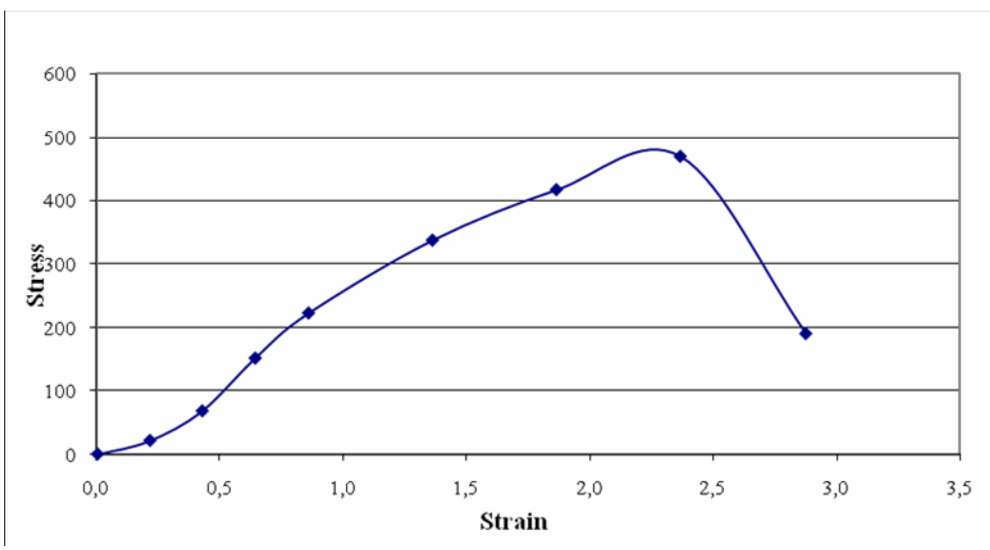
(mm)	3)		
0.0168	-1.4706	0.0168	-0.7490
0.2230	65.5883	0.2230	33.4039
0.4383	97.9413	0.4383	49.8811
0.6509	131.7649	0.6509	67.1073
0.8675	162.6473	0.8675	82.8356
1.3792	230.8826	1.3792	117.5876
1.8923	288.2356	1.8923	146.7972
2.4040	334.7063	2.4040	170.4645
2.9170	365.5887	2.9170	186.1928
3.4326	368.5299	3.4326	187.6907
3.9353	312.6474	3.9353	159.2300



UCS = 190 kPa

ii. Kaolin + 6% Lime

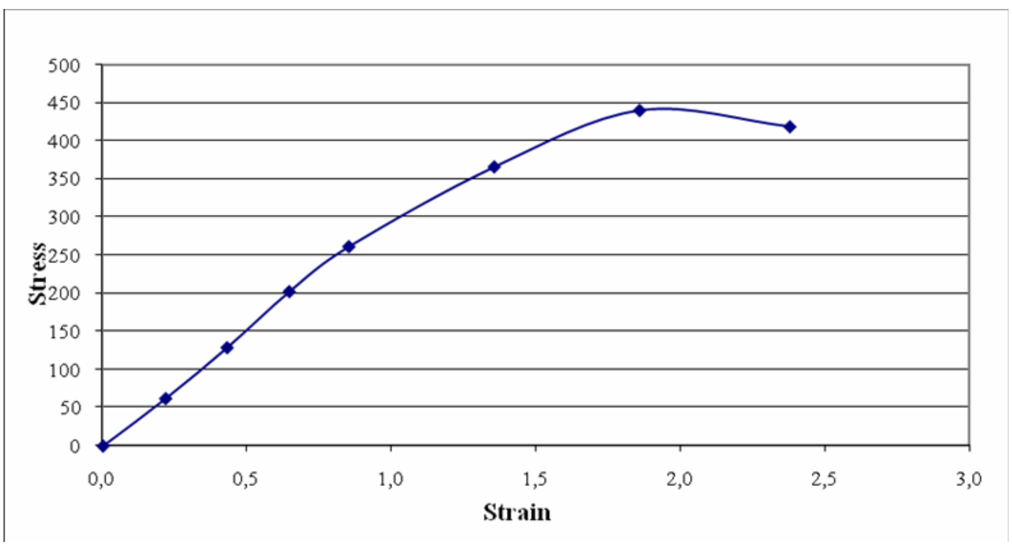
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2162	42.0589	0.2162	21.4204
0.4286	133.8237	0.4286	68.1558
0.6435	297.0592	0.6435	151.2910
0.8598	436.7652	0.8598	222.4427
1.3625	662.6479	1.3625	337.4838
1.8652	819.1186	1.8652	417.1737
2.3679	922.0599	2.3679	469.6013
2.8771	372.9416	2.8771	189.9376



UCS = 485 kPa

iii. Kaolin + 6% Lime + 5% Zeolite A

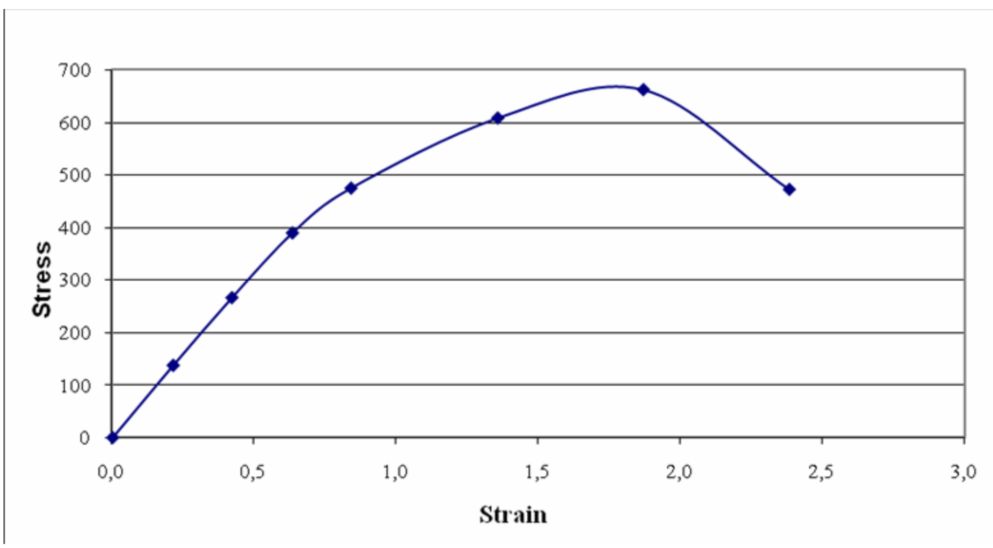
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0064	0	0.0064	0
0.2227	122.0590	0.2227	62.1641
0.4350	252.9415	0.4350	128.8220
0.6499	397.0593	0.6499	202.2206
0.8561	512.6477	0.8561	261.0893
1.3588	717.6479	1.3588	365.4951
1.8615	862.6481	1.8615	439.3431
2.3810	820.5892	2.3810	417.9227



UCS = 440 kPa

iv. Kaolin + 6% Lime + 10% Zeolite A

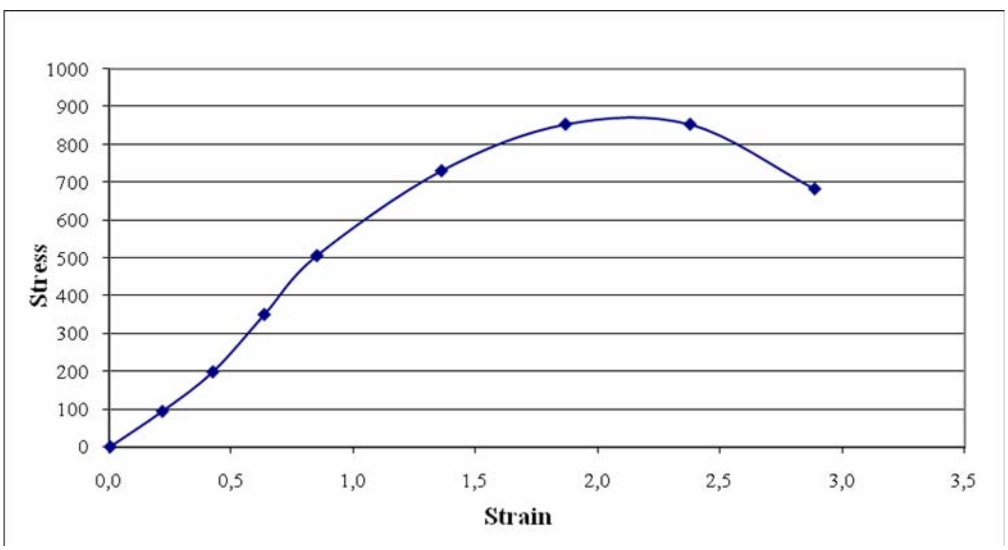
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2166	270.0003	0.2166	137.5100
0.4228	522.9418	0.4228	266.3321
0.6355	764.7068	0.6355	389.4620
0.8417	932.3541	0.8417	474.8440
1.3573	1194.119	1.3573	608.1599
1.8691	1300.0016	1.8691	662.0854
2.3821	927.3541	2.3821	472.2975



UCS = 670 kPa

v. Kaolin + 6% Lime + 15% Zeolite A

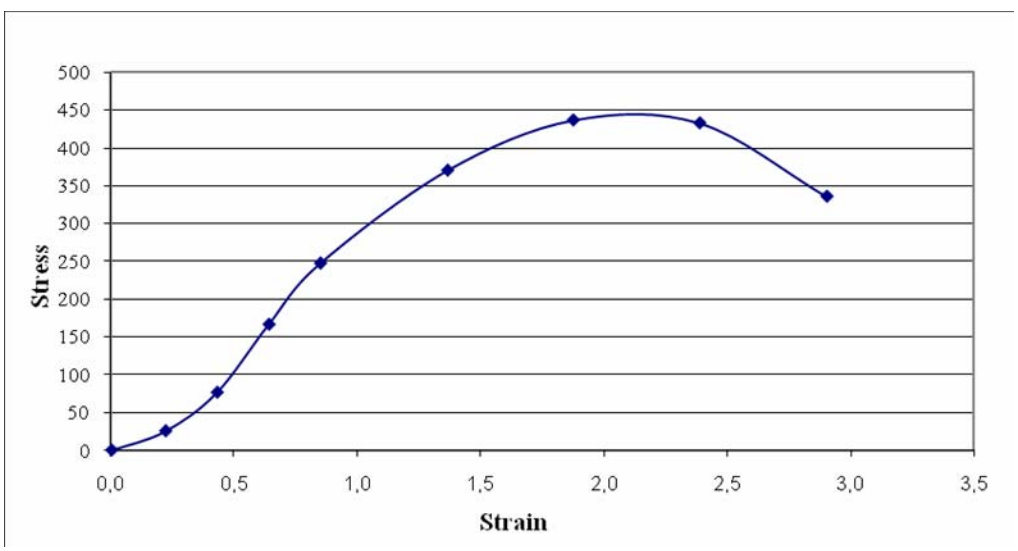
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0064	0.8824	0.0064	0.4494
0.2191	184.7061	0.2191	94.0700
0.4254	389.7064	0.4254	198.4758
0.6355	687.6479	0.6355	350.2162
0.8507	993.5306	0.8507	506.0010
1.3599	1434.7076	1.3599	730.6906
1.8665	1675.884	1.8665	853.5209
2.3756	1675.8844	2.3756	853.5209
2.8848	1340.5898	2.8848	682.7568



UCS = 875 kPa

vi. Kaolin + 6% Lime + 5% Zeolite B

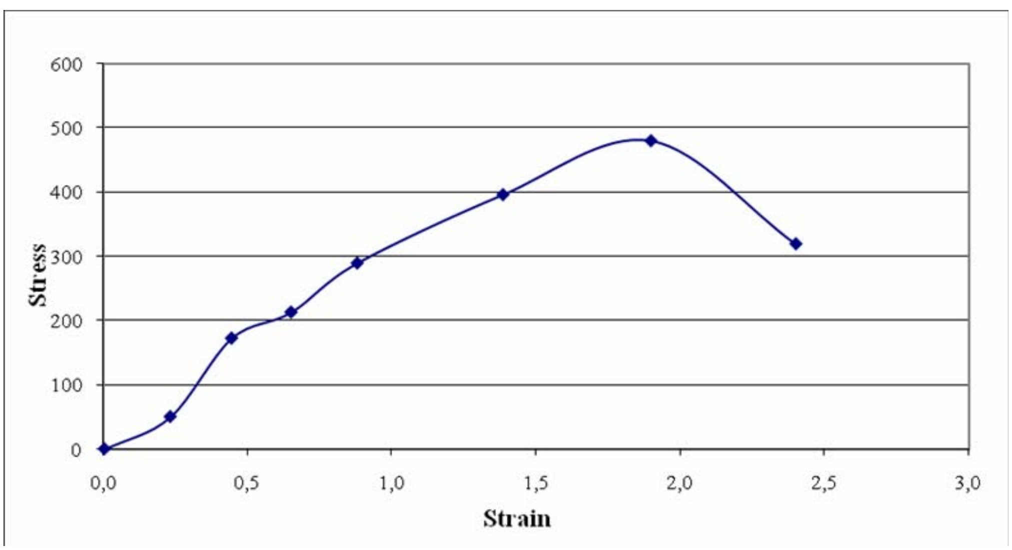
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2230	50.0001	0.2230	25.4648
0.4318	150.0002	0.4318	76.3945
0.6419	326.4710	0.6419	166.2703
0.8507	485.2947	0.8507	247.1586
1.3663	726.4715	1.3663	369.9889
1.8755	856.7657	1.8755	436.3472
2.3885	849.4128	2.3885	432.6024
2.9041	658.8243	2.9041	335.5365



UCS = 452 kPa

vii. Kaolin + 6% Lime + 10% Zeolite B

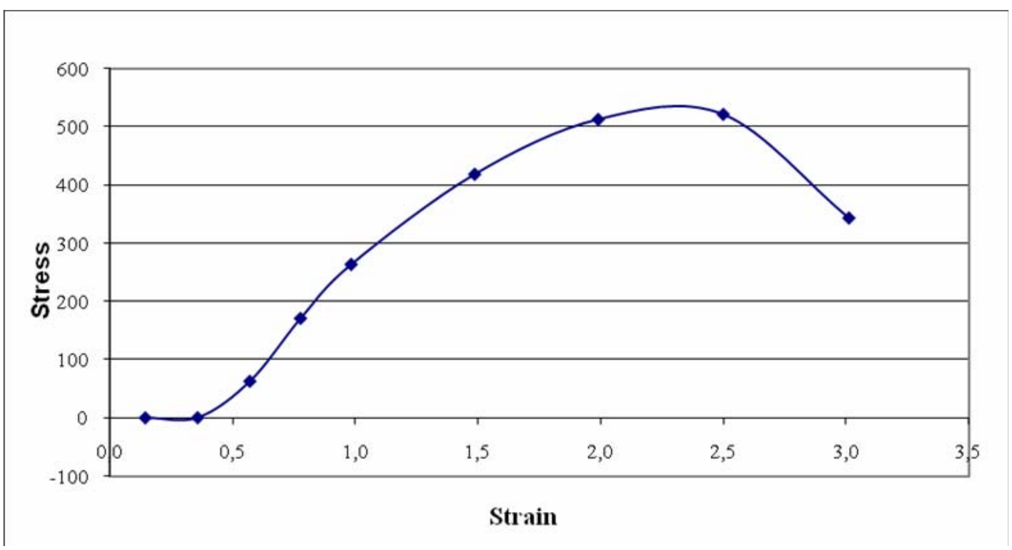
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2320	98.5295	0.2320	50.1807
0.4447	338.2357	0.4447	172.2620
0.6509	417.6476	0.6509	212.7062
0.8804	567.6477	0.8804	289.1006
1.3857	776.4715	1.3857	395.4537
1.8987	941.1776	1.8987	479.3378
2.4014	626.4713	2.4014	319.0592



UCS = 480 kPa

viii. Kaolin + 6% Lime + 15% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.1457	0.8824	0.1457	0.4494
0.3583	1.4706	0.3583	0.7490
0.5710	124.4119	0.5710	63.3625
0.7773	336.7651	0.7773	171.5131
0.9835	519.1183	0.9835	264.3848
1.4862	823.5304	1.4862	419.4206
1.9889	1008.825	1.9889	513.7902
2.4981	1025.8836	2.4981	522.4782
3.0098	675.8832	3.0098	344.2245

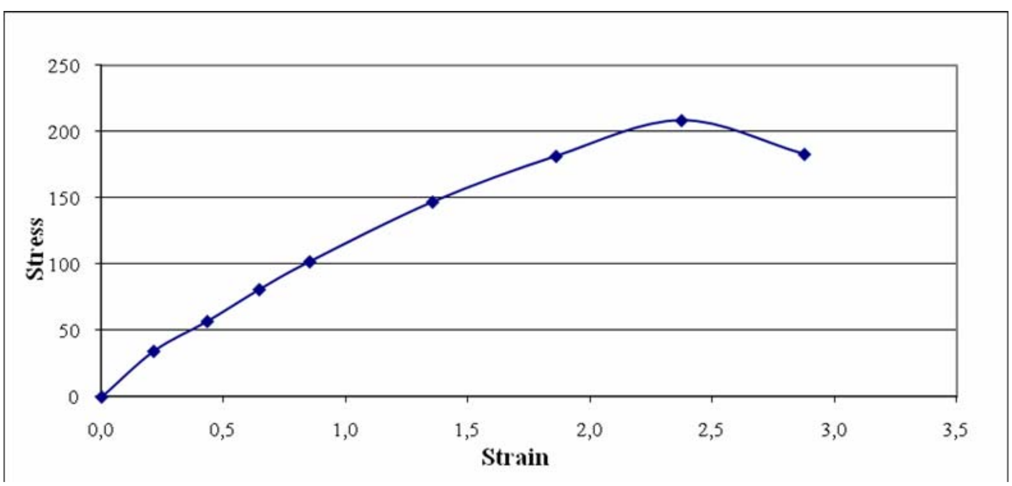


UCS = 542 kPa

APPENDIX C4: UNCONFINED COMPRESSION STRENGTH (28 DAYS)

i. Untreated Soil (Kaolin)

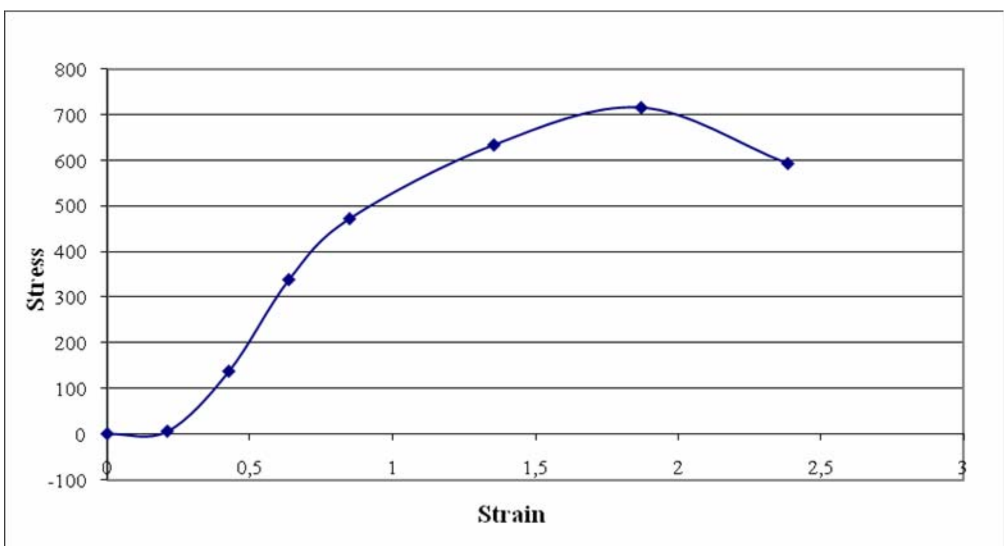
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	0.0039	0
0.2166	67.6471	0.2166	34.4524
0.4357	111.7648	0.4357	56.9214
0.6484	158.8237	0.6484	80.8883
0.8546	200.0002	0.8546	101.8593
1.3573	288.2356	1.3573	146.7972
1.8626	355.8828	1.8626	181.2496
2.3756	408.8240	2.3756	208.2124
2.8783	358.8240	2.8783	182.7475



UCS = 208 kPa

ii. Kaolin + 6% Lime

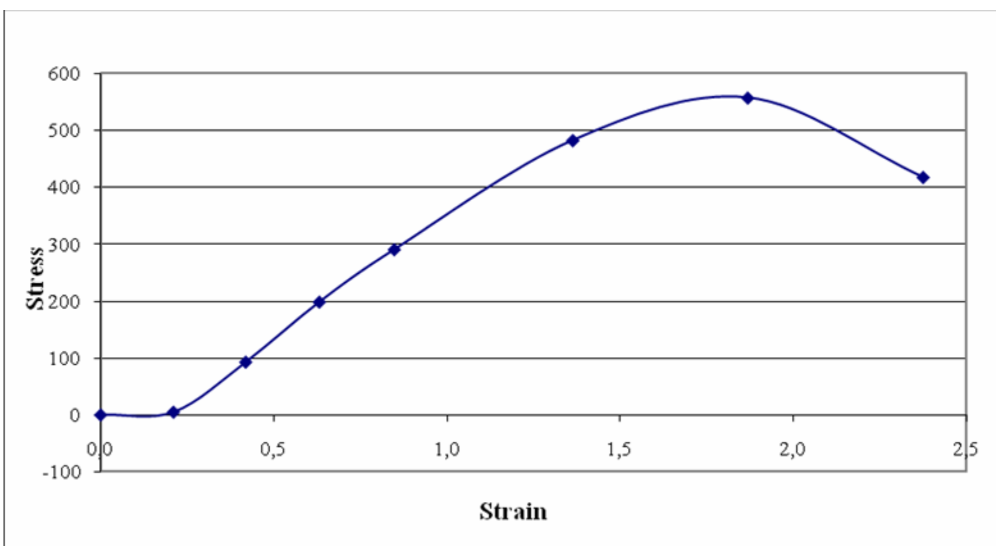
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	0	0
0.2101	11.1765	0.2101	5.6921
0.4254	270.0003	0.4254	137.5100
0.6355	665.5890	0.6355	338.9817
0.8482	928.8246	0.8482	473.0465
1.3535	1247.0603	1.3535	635.1226
1.8691	1408.2370	1.8691	717.2092
2.3821	1167.0602	2.3821	594.3789



UCS = 717 kPa

iii. Kaolin + 6% Lime + 5% Zeolite A

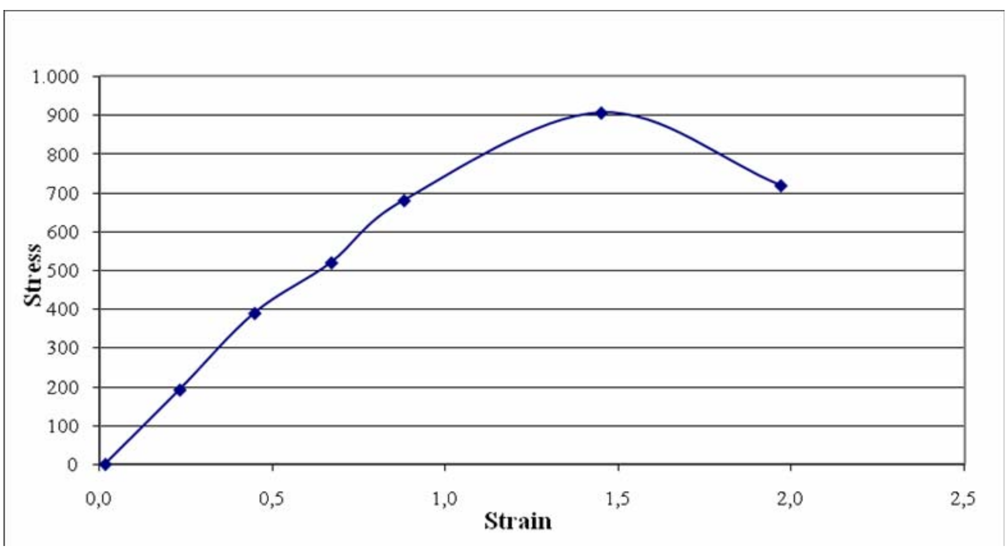
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	0	0
0.2101	9.7059	0.2101	4.9432
0.4189	182.3532	0.4189	92.8717
0.6316	389.7064	0.6316	198.4758
0.8482	570.5889	0.8482	290.5986
1.3638	947.0600	1.3638	482.3337
1.8691	1094.1190	1.8691	557.2302
2.3756	820.0010	2.3756	417.6231



UCS = 557 kPa

iv. Kaolin + 6% Lime + 10% Zeolite A

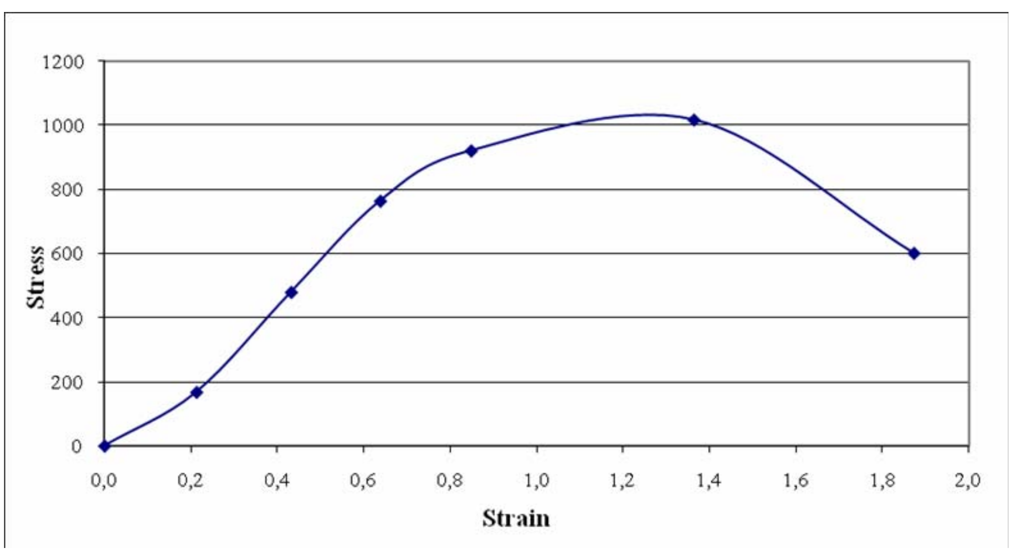
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0168	0	0.0168	0
0.2320	376.4710	0.2320	191.7351
0.4486	764.7068	0.4486	389.4620
0.6703	1020.5895	0.6703	519.7819
0.8804	1335.2957	0.8804	680.0605
1.4501	1779.4139	1.4501	906.2481
1.9696	1411.1782	1.9696	718.7071



UCS = 906 kPa

v. Kaolin + 6% Lime + 15% Zeolite A

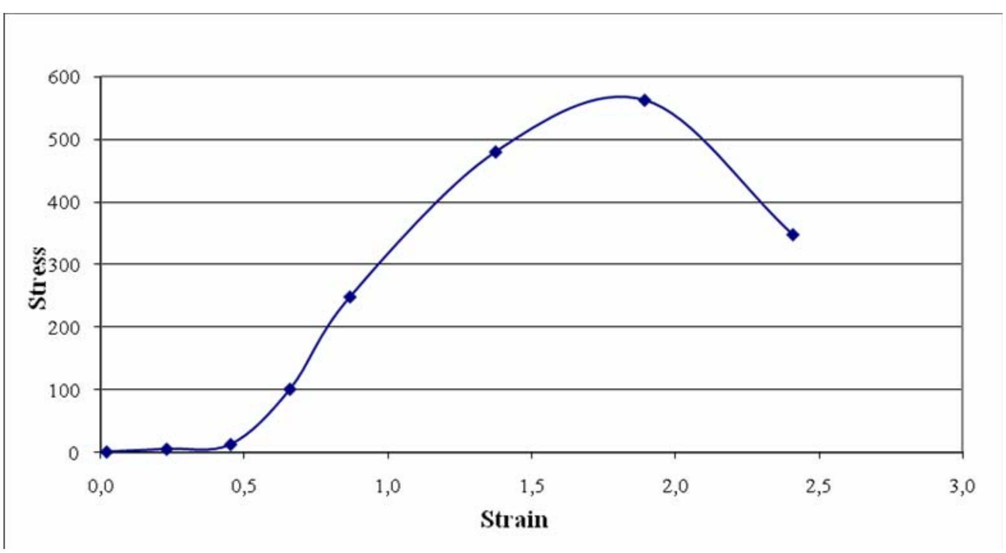
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	**0**	0
0.2127	328.8239	0.2127	167.4686
0.4318	940.5894	0.4318	479.0382
0.6381	1499.4136	0.6381	763.6451
0.8482	1807.355	0.8482	920.4784
1.3638	1996.4730	1.3638	1016.7953
1.8729	1180.2955	1.8729	601.1196



UCS = 1028 kPa

vi. Kaolin + 6% Lime + 5% Zeolite B

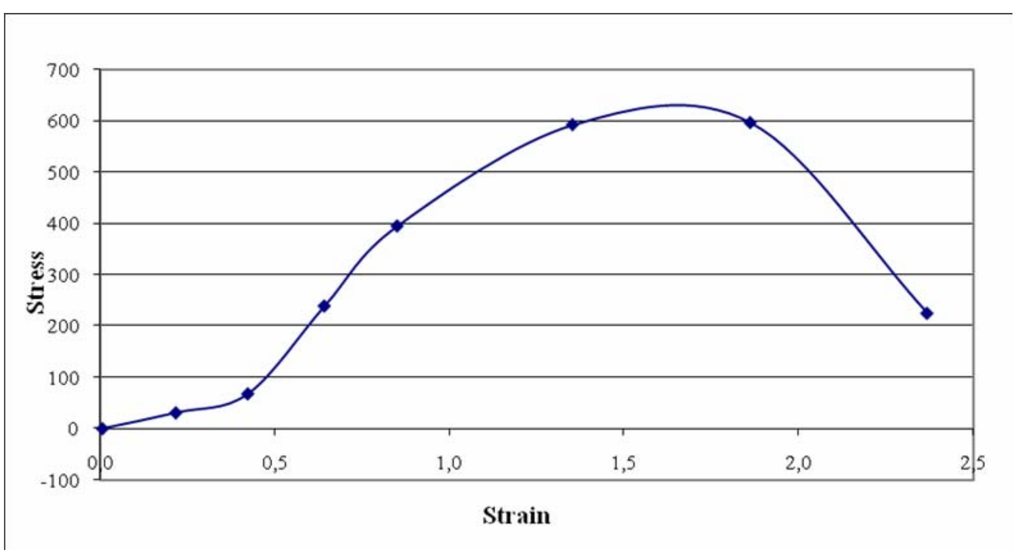
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0232	1.4706	0.0232	0.7490
0.2317	10.2941	0.2317	5.2428
0.4543	25.0000	0.4543	12.7324
0.6605	198.5297	0.6605	101.1103
0.8693	488.2359	0.8693	248.6565
1.3759	943.5305	1.3759	480.5362
1.8941	1105.8837	1.8941	563.2219
2.4097	683.8244	2.4097	348.2689



UCS = 567 kPa

vii. Kaolin + 6% Lime + 10% Zeolite B

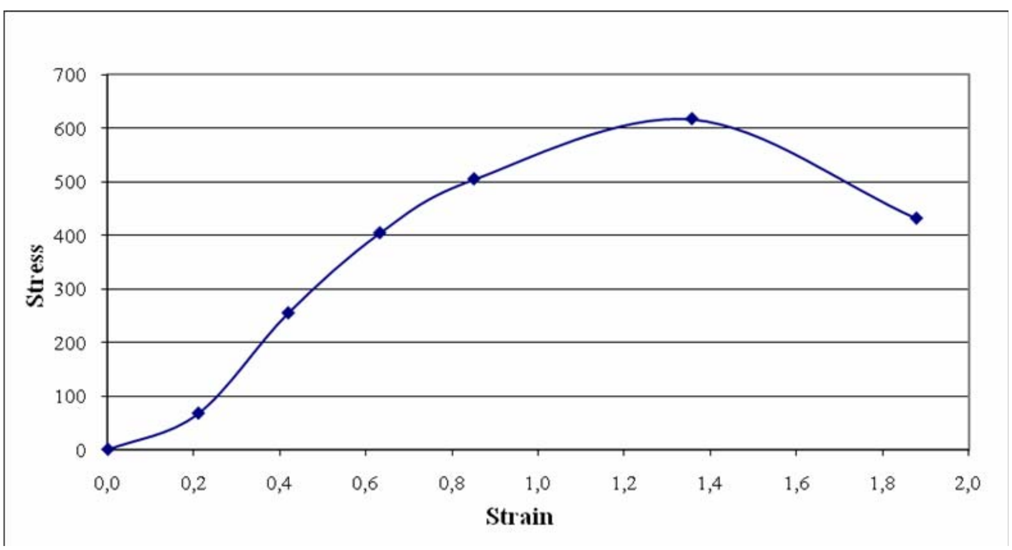
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0064	-0.8824	0.0064	-0.4494
0.2166	59.7060	0.2166	30.4080
0.4228	132.3531	0.4228	67.4069
0.6419	468.5300	0.6419	238.6204
0.8507	775.0009	0.8507	394.7047
1.3535	1162.6485	1.3535	592.1320
1.8626	1170.5896	1.8626	596.1764
2.3692	440.5888	2.3692	224.3900



UCS = 628 kPa

viii. Kaolin + 6% Lime + 15% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	0	0
0.2101	132.3531	0.2101	67.4069
0.4189	500.0006	0.4254	254.6482
0.6316	793.5304	0.6355	404.1417
0.8507	991.1777	0.8482	504.8026
1.3573	1211.7662	1.3535	617.1474
1.8794	847.0598	1.8691	431.4040

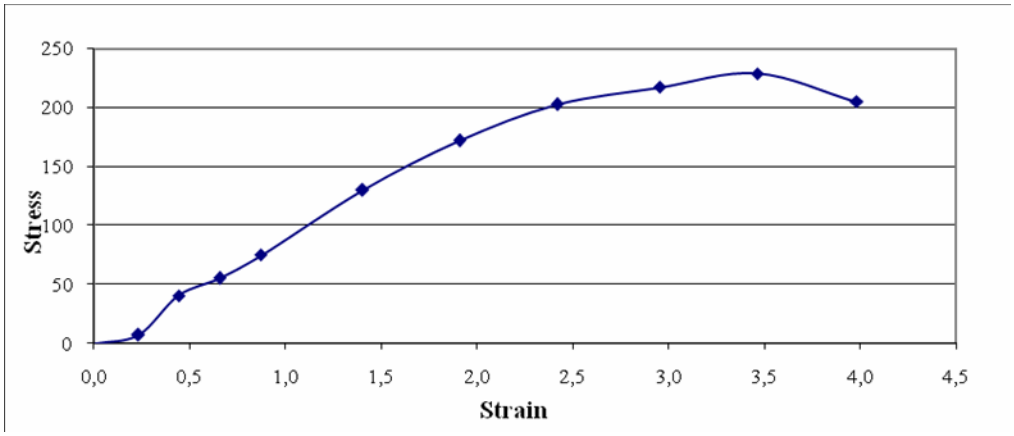


UCS = 617 kPa

APPENDIX C5: UNCONFINED COMPRESSION STRENGTH (56 DAYS)

i. Untreated Soil (Kaolin)

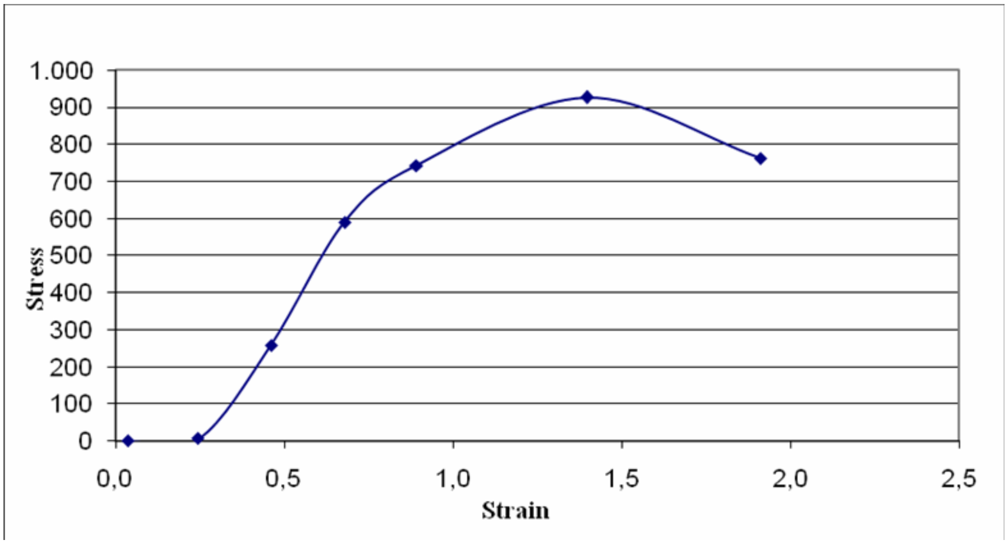
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0103	-0.8824	0.0103	-0.4494
0.2317	14.1177	0.2317	7.1901
0.4440	78.8236	0.4440	40.1445
0.6564	108.2354	0.6564	55.1238
0.8726	147.0590	0.8726	74.8965
1.4028	255.2944	1.4028	130.0204
1.9086	337.6475	1.9086	171.9624
2.4170	397.9417	2.4170	202.6700
2.9511	426.4711	2.9511	217.1999
3.4620	449.4123	3.4620	228.8838
3.9811	402.3534	3.9811	204.9169



UCS = 228 kPa

ii. Kaolin + 6% Lime

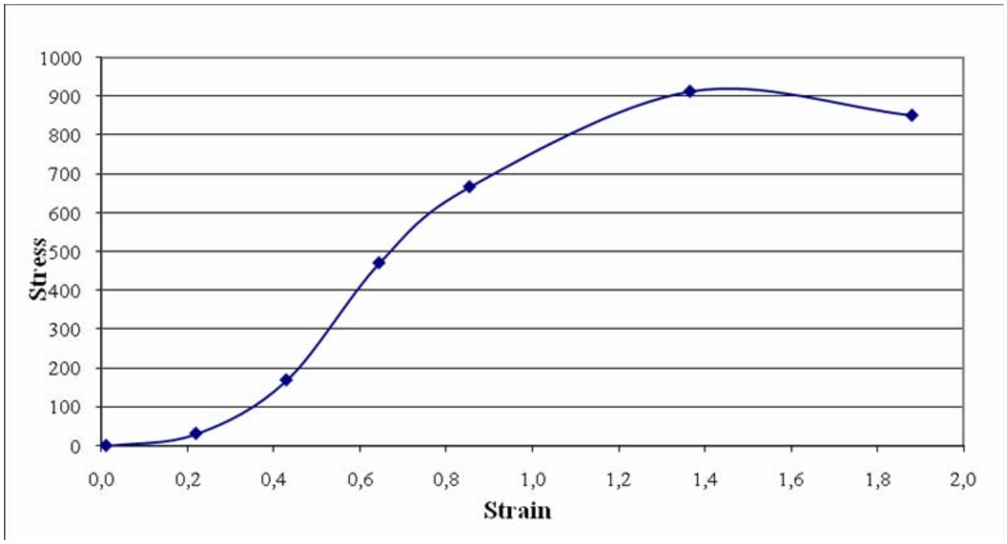
Axial Displacement, Δ L (mm)	**Compressive Load, P (kN x 10e-3)**	**Strain**	**Stress**
0.0360	0	0.0360	0
0.2445	13.2353	0.2445	6.7407
0.4607	507.3536	0.4607	258.3930
0.6795	1159.7073	0.6795	590.6341
0.8919	1459.7076	0.8919	743.4230
1.3964	1818.5316	1.3964	926.1705
1.9112	1495.5900	1.9112	761.6977



UCS = 926 kPa

iii. Kaolin + 6% Lime + 5% Zeolite A

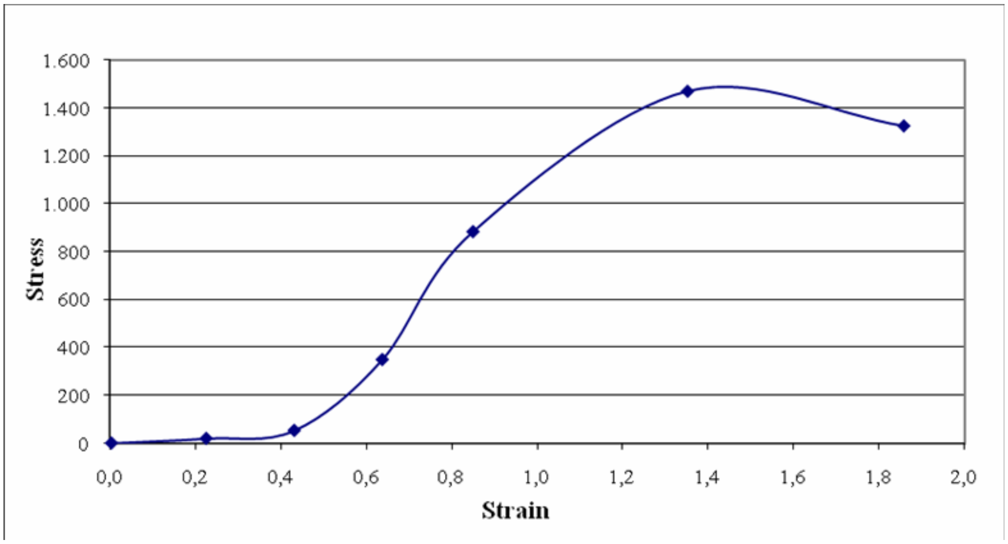
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0103	0.8824	0.0039	0.4494
0.2188	61.7648	0.2166	31.4565
0.4286	332.3533	0.4357	169.2662
0.6439	924.4129	0.6484	470.7996
0.8540	1308.8251	0.8546	666.5791
1.3657	1791.1786	1.3573	912.2398
1.8813	1670.0020	1.8626	850.5250



UCS = 924 kPa

iv. Kaolin + 6% Lime + 10% Zeolite A

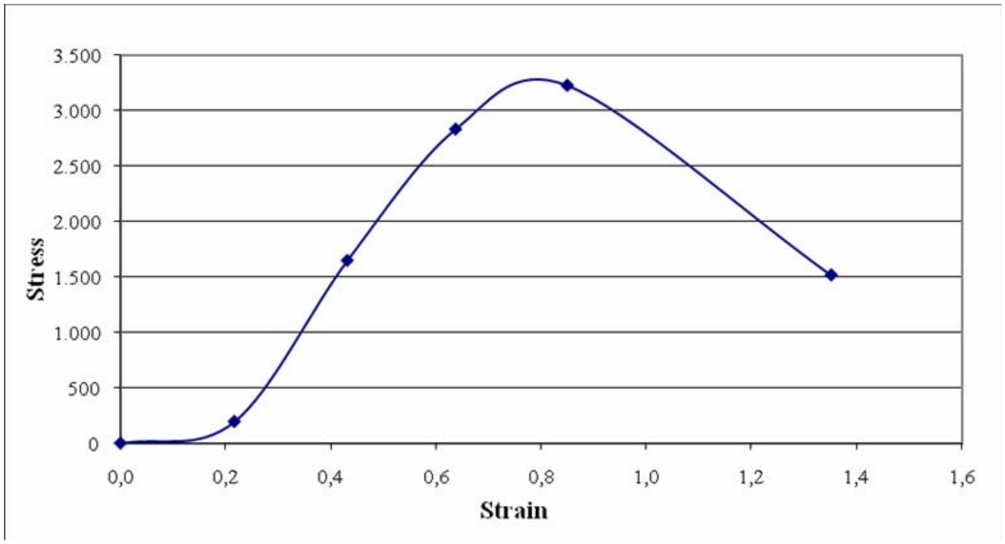
Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0039	0	**0.0039**	0
0.2252	38.2353	0.2252	19.4731
0.4311	103.8237	0.4311	52.8770
0.6371	685.2949	0.6371	349.0178
0.8494	1735.2962	0.8494	883.7791
1.3514	2886.7682	1.3514	1470.2190
1.8571	2602.3561	1.8571	1325.3691



UCS = 1481 kPa

v. Kaolin + 6% Lime + 15% Zeolite A

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0	0	0	0
0.2162	382.3534	0.2162	194.7310
0.4311	3234.7098	0.4311	1647.4242
0.6371	5561.7714	0.6371	2832.5869
0.8494	6337.6547	0.8494	3227.7410
1.3514	2978.8271	1.3514	1517.1042

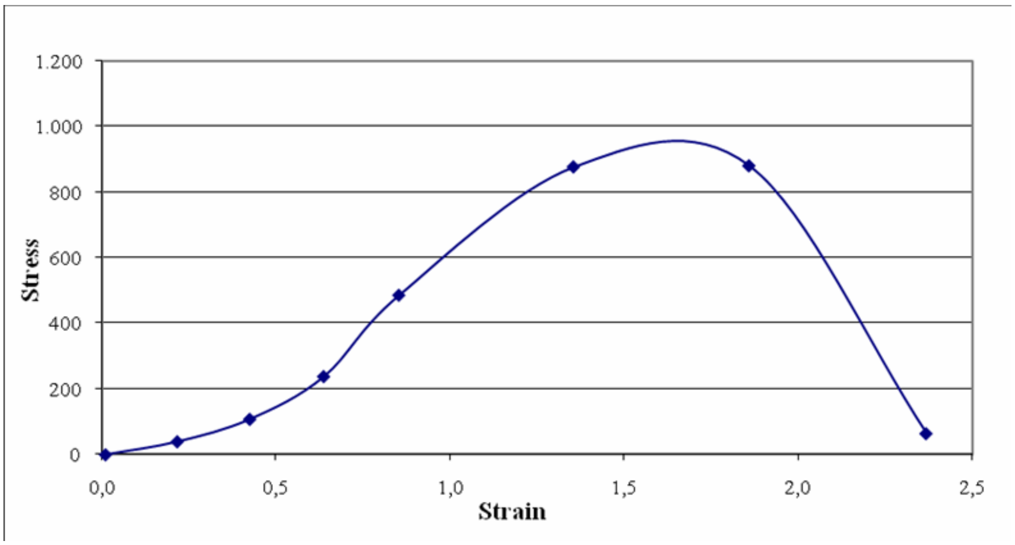


UCS = 3288 kPa

vi. Kaolin + 6% Lime + 5% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0103	0	0.0103	0
0.2162	77.9413	0.2162	39.6952
0.4247	212.6473	0.4247	108.3004
0.6371	468.5300	0.6371	238.6204
0.8533	955.8835	0.8533	486.8275

1.3552	1724.4138	1.3552	878.2368
1.8597	1730.8844	1.8597	881.5322
2.3688	126.4707	2.3688	64.4110

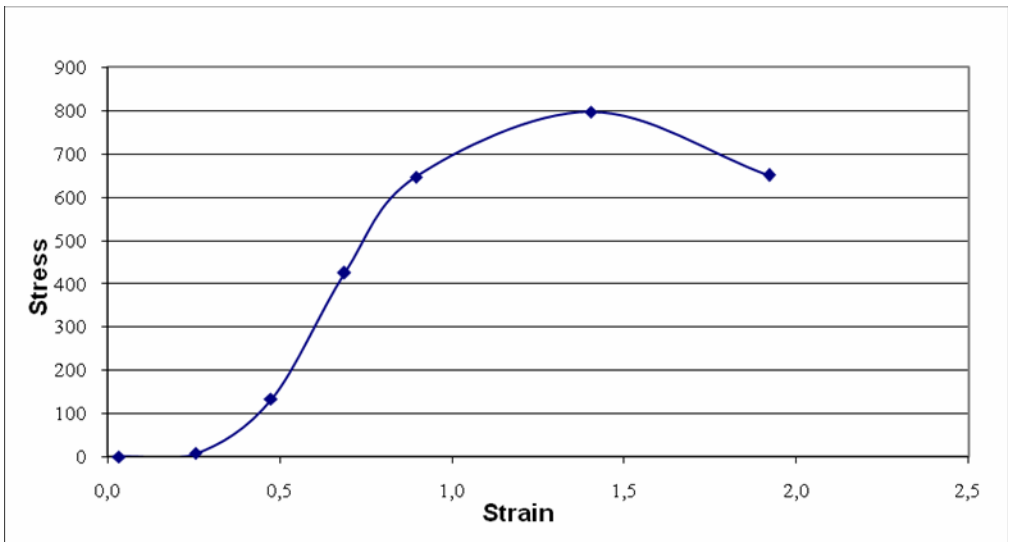


UCS = 982 kPa

vii. Kaolin + 6% Lime + 10% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress
0.0322	0.8824	0.0322	0.4494
0.2552	14.1177	0.2552	7.1901

0.4744	260.2944	0.4744	132.5669
0.6870	832.3539	0.6870	423.9144
0.8959	1268.5309	0.8959	646.0575
1.4024	1562.6489	1.4024	795.8506
1.9206	1275.8839	1.9206	649.8023

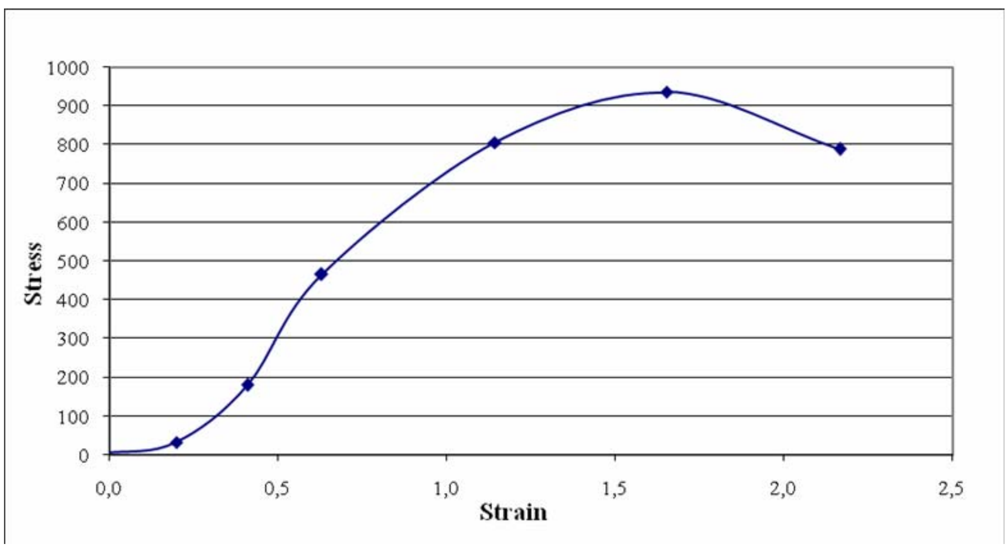


UCS = 797 kPa

viii. Kaolin + 6% Lime + 15% Zeolite B

Axial Displacement, Δ L (mm)	Compressive Load, P (kN x 10e-3)	Strain	Stress

-0.2162	2.9412	-0.2162	1.4979
-0.0103	14.1177	-0.0103	7.1901
0.1969	64.1177	0.1969	32.6549
0.4093	352.9416	0.4093	179.7517
0.6281	914.7070	0.6281	465.8564
1.1429	1582.3548	1.1429	805.8867
1.6512	1838.2375	1.6512	936.2067
2.1662	1550.0019	2.1662	789.4095



UCS = 936 kPa